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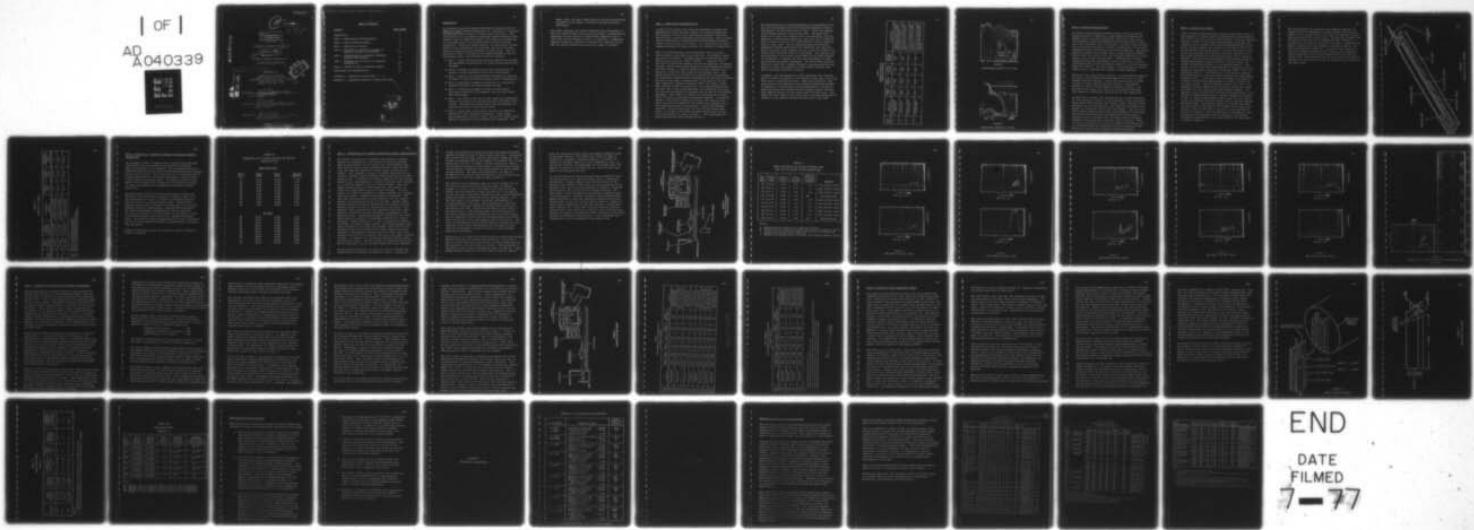
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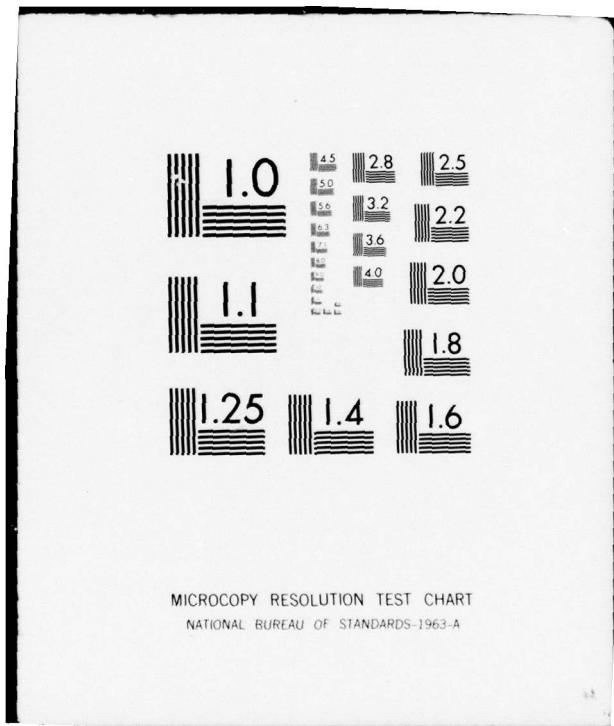
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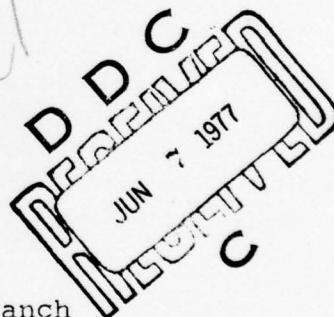
6 ON EVALUATION OF

LARGE PYROTECHNIC ARRAYS FOR
NUCLEAR BURST SIMULATION.

15 DAAG39-76-C-2002

Prepared For:

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INTRODUCTION

In accordance with Harry Diamond Laboratories Purchase Order No. DAAG39-76-C-2002, Unidynamics/Phoenix, Inc. performed an evaluation of large pyrotechnic arrays for nuclear burst simulation. This investigation was an extension of previous studies conducted under Purchase Order No. DAAC39-75-C-2006, during which the feasibility of using pyrotechnics as high-radiant-flux emitters had been established. During the current program, the development of high-radiant-output pyrotechnics was continued, and two of the more energetic compositions were evaluated in large arrays. The following major tasks, identified by the number assigned to each in the purchase order, were performed during this program.

- Task 1 - Using motion pictures and other appropriate methods, the smoke/plume characteristics of selected pyrotechnics were recorded.
- Task 2 - Methods of dispersing the smoke generated by the burning of large pyrotechnic arrays were investigated.
- Task 3 - Ignition aid techniques were developed for igniting all parts of large pyrotechnic surfaces nearly simultaneously.
- Task 4 - Pyrotechnic samples were provided to a designated Government facility for radiant output testing.
- Task 5 - Alternate pyrotechnic burning configurations, particularly ignition on the opposite side from the target, were investigated.
- Task 7 - The state of the art in high temperature pyrotechnic research was monitored to identify possible new radiant flux sources. Laboratory irradiance tests were performed on all compositions deemed to have special merit.
- Task 8 - Three large arrays each of the two most promising pyrotechnics were constructed and tested. These arrays had an equivalent effective surface area of 28.3 square inches and were configured to allow optimum smoke dispersal. The

plume, smoke, and other characteristics of the six burns were recorded by still camera, television, and motion picture photography.

This report describes the results obtained during performance of the seven numbered tasks and presents Unidynamics' recommendations concerning the safe handling of pyrotechnic components used in very large nuclear simulation arrays. In addition, a comparative summary of pertinent laboratory irradiance data obtained during both the current program and the previous study is included.

TASK 1 - SMOKE/PLUME CHARACTERIZATION

A series of six outdoor burn tests was performed to observe and photograph the smoke and plume effects of selected pyrotechnics. The materials evaluated were magnesium/Halon/Fluorel (1960 Mix, Lot EL 37070), zirconium/molybdenum trioxide/Fluorel (Lot EL 37059), and two formulations of magnesium/zirconium/molybdenum trioxide/Fluorel (Lots EL 40104 and EL 40105). The constituents and major combustion products of these materials are tabulated in Appendix A.

Both 35 mm black-and-white still photographs and 16 mm color motion pictures were taken during each test. In addition, pellet burn time was recorded. The data obtained and observations made during the six tests are listed in Table I. Figures 1 and 2 show typical smoke/plume effects from the two materials of greatest interest, 1960 Mix and Fluorel-bonded zirconium/molybdenum trioxide. As noted in Table I, 1960 Mix produced a small yellowish-white plume and a relatively thin cloud of grayish-white smoke. The yellow coloration in the plume can be attributed to the presence of incandescent carbon particles functioning as black body radiators. The color of the smoke is proportional to the ratio of its two major components, magnesium fluoride (white) and carbon (black). When 1960 Mix is burned in excess air, as in the reported series of tests, most of the carbon particles are consumed as they leave the fuel-rich environment of the plume and mix with the surrounding atmosphere. This causes the smoke to be grayish-white in color since its primary constituent is magnesium fluoride. In addition, removal of the carbon significantly reduces the density of the smoke from 1960 Mix compared to that produced by compositions of the zirconium/molybdenum trioxide type. Of the four materials evaluated, 1960 Mix produced by far the least obscuring smoke cloud. An example of the smoke and plume effects from a pellet of burning 1960 Mix is shown in Figure 1. This photograph was taken approximately midway through the burn.

The plumes produced by zirconium/molybdenum trioxide/Fluorel and the two Fluorel-bonded magnesium/zirconium/molybdenum trioxide formulations were brilliant white in color. Plume size appeared to be directly related to pellet burn rate. The plume from a pellet of EL 37059 (all zirconium fuel) was moderately long and expansive, reflecting the medium fast burn rate of this material. Also, as shown in Figure 2, EL 37059 produced a dense, obscuring cloud of white smoke. The two magnesium-modified zirconium/molybdenum trioxide formulations both exhibited very fast burn rates, resulting in the formation of long, broad jet plumes which evolved into very dense clouds of white smoke. The combined size and brilliance of the plumes from EL 40104 and EL 40105 resulted in illumination so intense that the still photographs of these two materials were badly overexposed. The color motion pictures, which were taken from a greater distance, disclosed that these compositions burned very rapidly with much greater violence than that of the other materials evaluated.

In summary, the reported series of tests disclosed that 1960 Mix burned in excess air produces a concentrated plume and a relatively thin cloud of grayish-white smoke. Under most conditions, this smoke would not be expected to cause serious obscuration problems. By comparison, Fluorel-bonded zirconium/molybdenum trioxide and magnesium/zirconium/molybdenum trioxide produce larger, brighter, more expansive plumes and very dense clouds of white smoke. The smoke from these compositions could easily cause severe obscuration problems if not properly removed from the area of the plume.

TABLE I
SMOKE/PLUME EFFECTS OF
SELECTED PYROTECHNICS

Test No.	Composition	Pellet Weight (gm)	Pellet Thickness (in)	Pellet Density (gm/cm ³)	Pellet Burn Rate (in/sec)	Observations
1	Mg/Halon/Fluorel Lot EL 37070 (1960 Mix)	15.01 15.07	0.390 0.384	1.91 1.95	0.03 0.03	Plume was ~ 6 inches in length and yellowish-white in color. Smoke was relatively thin and grayish-white in color.
2	Zr/MoO ₃ /Fluorel Lot EL 37059	19.80 19.84	0.255 0.254	3.86 3.88	0.11 0.12	Plume was ~ 12 inches in length and brilliant white in color. Smoke was dense and white in color.
3	Mg/Zr/MoO ₃ /Fluorel Lot EL 40104	20.16	0.351	2.85	0.70	Plume was ~ 24 inches in length and brilliant white in color. Smoke was very dense and white in color.
4	Mg/Zr/MoO ₃ /Fluorel Lot EL 40105	19.92	0.396	2.50	0.79	Plume was ~ 24 inches in length and brilliant white in color. Smoke was very dense and white in color.



FIGURE 1
SMOKE/PLUME EFFECTS OF 1960 MIX

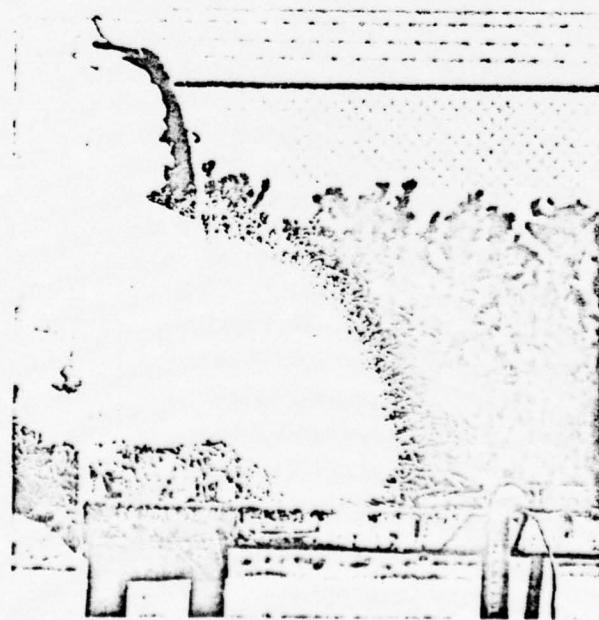


FIGURE 2
SMOKE/PLUME EFFECTS OF Zr/MoO₃

TASK 2 - SMOKE DISPERSAL METHODS

The primary smoke dispersal method evaluated during the current program consisted of operating a large exhaust fan adjacent to parallel panels of burning pyrotechnic comprising a test array. This technique, which was employed during the two series of large array tests conducted late in the program, created a rapid air flow over the parallel pyrotechnic surfaces, sweeping most of the solid combustion products and residue away from the aperture. Pyrotechnic materials evaluated during these tests included magnesium/Halon/Fluorel (1960 Mix, Lot EL 37070) and zirconium/molybdenum trioxide/Fluorel (Lots EL 37059 and EL 40130). Although both of these compositions generate considerable smoke on combustion, the zirconium/molybdenum trioxide formulation produces a far more obscuring cloud than 1960 Mix. For this reason, it was regarded as the most likely source of problems with respect to smoke dispersal.

During the first test series, in which a 2.5-inch diameter aperture was used, a four-bladed Unidynamics-supplied fan with a 20-inch diameter sweep was employed. During the second series of tests, in which a 6-inch diameter aperture was used, a four-bladed Peerless fan with a 36-inch diameter sweep was utilized. The fan used in the latter test series was a Government-furnished item supplied to Unidynamics specifically for this application.

In both series of tests, the fan selected for use had sufficient air flow capacity to remove a large percentage of the particulate matter which would otherwise have formed a dense, obscuring cloud of smoke in or near the aperture, thus blocking the radiant flux between the pyrotechnic emitter and the detector. The peak irradiance values recorded during these tests compared very favorably with those obtained for the same compositions during earlier laboratory tests, indicating that the smoke removal techniques employed in the large array tests were highly effective. Thus, it can be concluded that the use of a properly sized exhaust fan is a suitable method for dispersing the smoke generated by the burning of a large array of parallel pyrotechnic panels.

TASK 3 - IGNITION AID STUDIES

Prior to testing large pyrotechnic arrays in the light tunnel, it was necessary to develop a means of igniting these items rapidly and reliably over their entire burning surface. With this objective in mind, a series of three tests was performed to evaluate the combined use of a surface layer of titanium/boron/Fluorel as the pellet ignition material and a length of pyrotechnic flash cord as the ignition transfer mechanism. The first two tests in this series were performed using pellets containing 1960 Mix as the base charge and 68/30/2 titanium/boron/Fluorel as the ignition material. The third test was conducted using pellets containing zirconium/molybdenum trioxide/Fluorel as the base charge and 65/30/5 titanium/boron/Fluorel as the ignition material. The pellets for all three tests were prepared by copressing the base charge and the ignition material at 5,000 psi (Tests 1 and 2) or 10,000 psi (Test 3). The composition of the ignition material was modified prior to the third test to improve its consolidation characteristics. In all three tests the pellets were aligned in a linear array measuring approximately 16 inches in length and one inch in width. Pellet thickness averaged 0.110 inch. The individual pellets comprising the array were aligned end to end and bonded to a base board using nitrocellulose lacquer. The ignition surface of the pellet array was also painted with a thin coating of nitrocellulose lacquer, and the assembly was allowed to dry. A length of pyrotechnic ignition cord was then secured to the top surface of the pellet array using a strip of aluminum foil-backed tape. The tape was applied in a manner which held the cord firmly in place against the surface of the array while leaving a space on each side of the cord to allow pressure to build up on ignition. This configuration was designed to cause a rapid flash to propagate along the length of the assembly. The general configuration of the three ignition aid test panels is shown in Figure 3.

The three ignition aid assemblies were tested by igniting the exposed end of the pyrotechnic cord and measuring the time required for the resultant flash to transmit the ignition stimulus along the length of the pellet array. The ignition transfer time was monitored by means of two ionization probes located at a measured interval above the surface of the array. Pertinent component parameters and data obtained in the three ignition aid tests are presented in Table II. As will be seen, the use of 0.125-inch diameter extended 50-4052 ignition cord resulted in rapid propagation of the ignition stimulus with both 1960 Mix and EL 37059. Based on the results of these tests, this type of ignition cord was selected for use in the large array testing in the light tunnel.

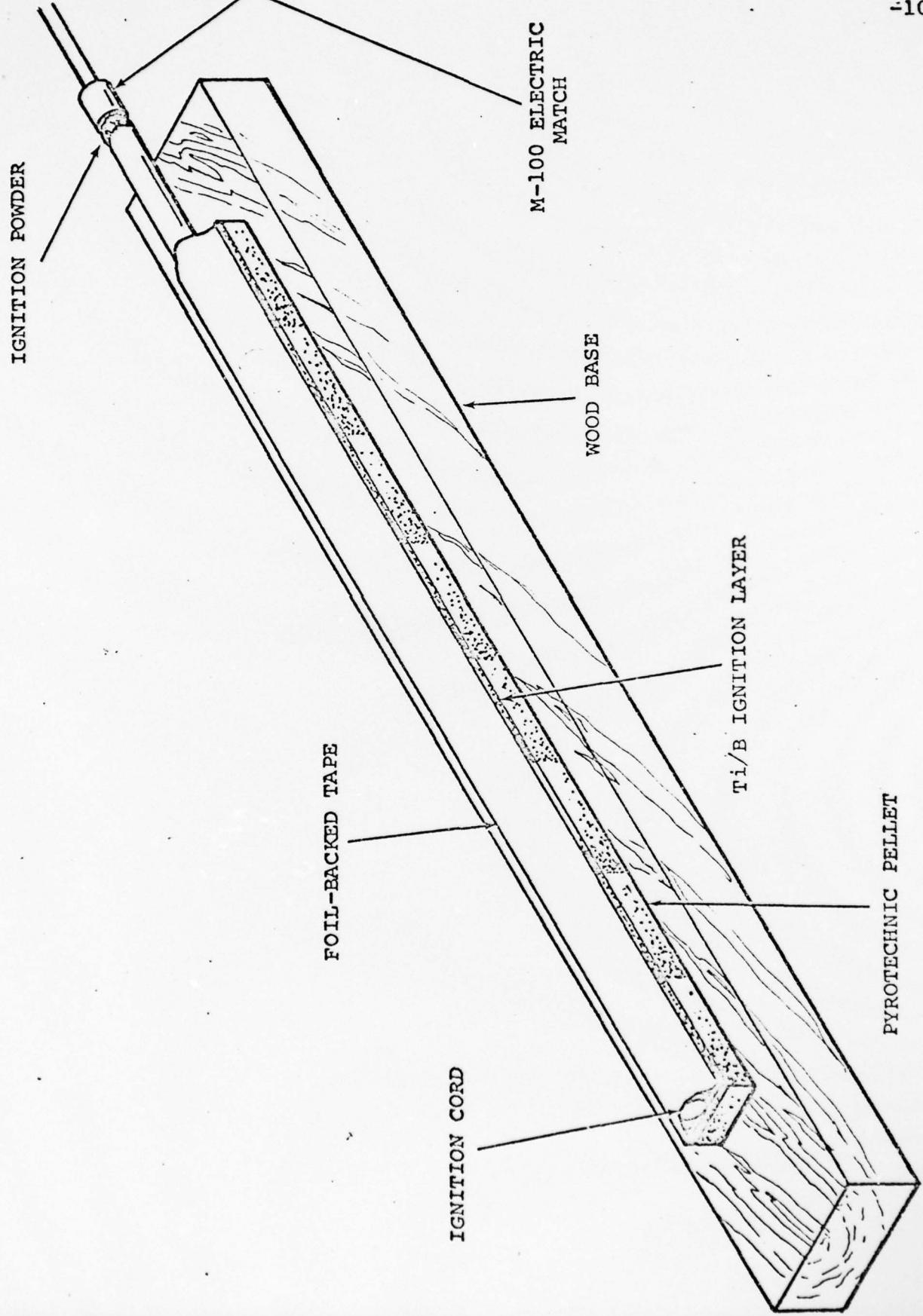


FIGURE 3
IGNITION AID TEST ASSEMBLY

TABLE II
IGNITION AID TESTS

Test No.	Pellet Base Material/ Weight	Pellet Ignition Material/ Weight	Pyrotechnic Cord Material	Length of Pellet Array (in)	Ignition Transfer Time (ms)	Ignition Propagation Rate (in/sec)
1	1960 Mix/ 5 grams	EL 40106/ 1 gram(1)	0.070-in diameter extruded 1340 Mix(3)	16.0	880.88	18.2
2	1960 Mix/ 5 grams	EL 40106/ 1 gram	0.125-in diameter extruded 50-4052 (4)	16.0	187.03	85.5
3	EL 37059/ 10 grams	EL 40113/ 1 gram(2)	0.125-in diameter extruded 50-4052	15.0	122.35	122.6

(1) 68/30/2 titanium/boron/Fluorel
 (2) 65/30/5 titanium/boron/Fluorel
 (3) 60/32.5/7.5 magnesium/Teflon/Fluorel
 (4) 60/30/5/5 magnesium/Halon/Fluorel/Pb₃O₄

TASK 4 - PROVISION OF PYROTECHNIC SAMPLES TO BALLISTIC RESEARCH LABORATORIES

At the request of HDL, 10 samples each of the two most promising high-radiant-output pyrotechnics were provided to Ballistic Research Laboratories for evaluation. The two compositions provided were 1960 Mix (Lot EL 37070) and zirconium/molybdenum trioxide/Fluorel (Lot EL 37059). Ten 1.0-inch wide by 1.5-inch long pellets of each formulation were fabricated and mounted on 2-inch square transite panels using epoxy cement. The exposed surface of each pellet was then painted with a coating of nitrocellulose lacquer to reduce the probability of chipping and to enhance ignition sensitivity.

The consolidation pressure used for both groups of pellets was 10,000 psi. The 1960 pellets contained 4.0 grams of 1960 Mix as the base charge and 0.5 gram of 65/30/5 titanium/boron/Fluorel (Lot EL 40113) as a copressed ignition layer. These pellets measured approximately 0.10 inch in thickness and had an average composite density of approximately 1.80 grams/cubic centimeter. The zirconium/molybdenum trioxide/Fluorel pellets contained 17.5 grams of EL 37059 as the base charge and 1.0 gram of 65/30/5 titanium/boron/Fluorel (Lot EL 40113) as a copressed ignition layer. These pellets measured approximately 0.20 inch in thickness and had an average composite density of approximately 3.65 grams/cubic centimeter.

Complete dimensional data for the 20 pellets supplied to BRL are listed in Table III.

TABLE III
DIMENSIONAL DATA FOR HIGH-RADIANT-FLUX PELLETS
SUPPLIED TO BRL

1960 COMPOSITION

Pellet No.	Weight (gm)	Height (in)	Density (gm/cm ³)
01	4.45	0.101	1.79
02	4.46	0.102	1.78
03	4.44	0.102	1.77
04	4.46	0.101	1.80
05	4.48	0.100	1.82
06	4.46	0.101	1.80
07	4.46	0.099	1.83
08	4.45	0.101	1.79
09	4.46	0.100	1.81
10	4.43	0.102	1.77

EL 37059

02	18.33	0.206	3.62
04	18.30	0.202	3.68
05	18.23	0.202	3.67
06	18.35	0.202	3.69
07	18.37	0.205	3.64
08	18.31	0.202	3.68
09	18.31	0.204	3.64
10	18.35	0.202	3.69
11	18.38	0.203	3.68
12	18.33	0.204	3.65

TASK 5 - INVESTIGATION OF ALTERNATE PYROTECHNIC BURNING CONFIGURATIONS

The initial screening of all candidate pyrotechnics as radiant emitters was performed in a test fixture in which the pellets were oriented parallel to the viewing axis of the detector head. Since pellets tested in this configuration were viewed from the side, the flame was observed at a point normal to the burning surface. This frequently resulted in partial obscuration of the flame by condensed combustion products downstream from the primary reaction zone. In addition, the output signatures of most pellets tested in this setup appeared as irradiance plateaus which remained at a relatively constant level for several seconds. Thus, the output characteristics of these pellets were more typical of a flare than a high-intensity burst of short duration. For this reason, in an effort to simulate the output signature of a nuclear burst more closely, a modified test method was developed. This test mode involved mounting a pellet directly over the viewing aperture and igniting the pellet from the back. Radiant output was then monitored during the period while the reaction zone was emerging through the front or viewing side of the pellet. This permitted direct observation of the unobscured flame for a short period of time before the reaction products accumulated in the downstream plume. Preliminary testing of 1960 Mix by this "back-burn" method was reported in Unidynamics Document No.'s MCD-23 and MCD-27 (Progress Report No.'s 3 and 5 for HDL PO No. DAAC39-75-C-2006). As stated in those reports, the maximum radiant output levels obtained by this method were somewhat lower and much less consistent than those obtained by the normal side-on test mode. Subsequent investigations disclosed that the reaction zone which emerged from the front of a burning 1960 pellet was highly irregular in shape. In addition, the reaction burn-through pattern varied from pellet to pellet. For this reason, the observed emitting area was not consistent, and very erratic output levels were obtained.

During the current program, an effort was made to eliminate the inconsistencies associated with backburn testing. A series of

10 tests was performed in which the pellets were mounted directly against the aperture plate to form a light-tight seal. The pellets were ignited from the back, and the flame front emerging on burn-through was monitored both by the radiant flux detector and a 16 mm motion picture camera. In order to permit simultaneous observation by both the detector and the camera, an optical beam splitter of 78.5 percent transmission was placed between the pellet holder and the detector. The camera was positioned at an angle of 90 degrees to the optical bench and focused on the surface of the beam splitter. This test setup is shown in Figure 4.

The results of the 10 backburn tests are listed in Table IV, and the flux-time traces from these tests are shown in Figures 5 through 9. As will be seen, the output curves were all highly erratic with the exception of those from Test No.'s 176 and 182. In those two tests, the pellets burned out on the sides and generated plumes much larger than the area of the viewing aperture. The last four tests in the backburn series were photographed at 64 frames/second on color film. The resulting films were scrutinized for evidence of combustion characteristics peculiar to the backburn test mode. During initial study of these films, it was observed that a high-intensity pulse of radiant energy of very short duration occurred immediately prior to pellet burnout. The full magnitude of this pulse was not delineated by the strip chart recorder due to the slow response time of this device. However, the oscilloscope reacted quickly enough to display the full intensity of this pulse, demonstrating the necessity of using this type of equipment to record the output of short-duration radiant burst phenomena.

Observation of the films also disclosed that the pellet burn-through patterns were extremely erratic and inconsistent. Oscillating pulses of light alternating with periods of reduced flame activity were apparent in all tests which were filmed. This phenomenon is illustrated by the series of photographs shown in Figure 10. These photographs were taken from the film record of Test No. 181 and

cover the time period during which the maximum irradiance level of that test occurred. The radiant peak, which is shown in Frame 612.4, represents a measured output of 4.4 mw/cm^2 and occurred at the point indicated on the accompanying trace. As can be seen from both the photographs and the output trace, the apparent irradiance of the pellet was at a very low level just prior to and following this peak.

In view of the erratic data generated during the backburn tests, the significance of the resulting output traces is considered questionable. However, based on the combined results of the backburn tests conducted during both the current program and the previous study, the use of this technique to achieve a simulated high-intensity radiant burst does not appear promising. For this reason, further evaluation of the backburn combustion mode is not recommended. Alternate pyrotechnic configurations which appear particularly useful for generating high-intensity bursts include those in which the burning surface contains a number of small concave indentations of some type (conical, inverted pyramidal, waffled, etc.) This type of surface geometry could be combined with a thin pellet web to obtain a very large effective burning area capable of yielding an output signature of very short duration and extremely high intensity. It is recommended that investigative efforts be pursued in this general area.

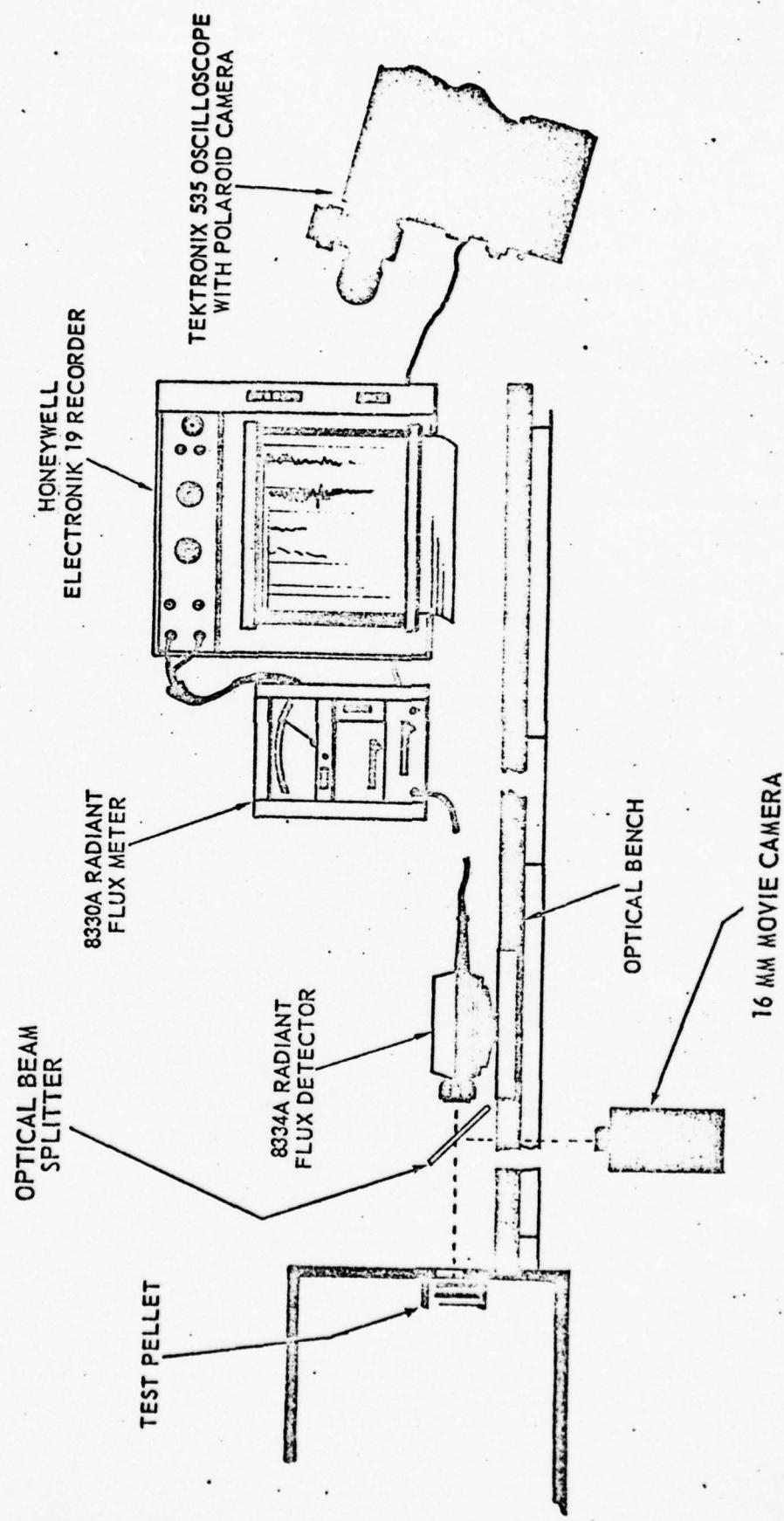


FIGURE 4
RADIANT FLUX TEST SETUP
(BACK BURN MODE)

TABLE IV
PELLET PROPERTIES AND RADIANT EMITTANCE DATA
FOR 1960 MIX TESTED IN THE BACKBURN MODE

<u>Test No. (S/N)</u>	<u>Pellet Weight (gm)</u>	<u>Pellet Thickness (in)</u>	<u>Pellet Density (gm/cm³)</u>	<u>Maximum Measured Irradiance (mw/cm²)</u>	<u>Remarks</u>
173	15.01	0.379	1.97	3.8	Very erratic trace
174	15.00	0.379	1.97	7.1	Very erratic trace
175	14.97	0.379	1.97	7.8	Very erratic trace
176	14.98	0.380	1.97	>20	Off-scale peak
177	15.00	0.379	1.97	4.4	Very erratic trace
178	15.00	0.378	1.97	9.8	Very erratic trace
179	15.02	0.379	1.97	3.3	Very erratic trace
180	14.97	0.380	1.97	5.6	Very erratic trace
181	14.89	0.377	1.96	4.4	Very erratic trace
182	15.01	0.379	1.97	>20	Off-scale peak

Notes:

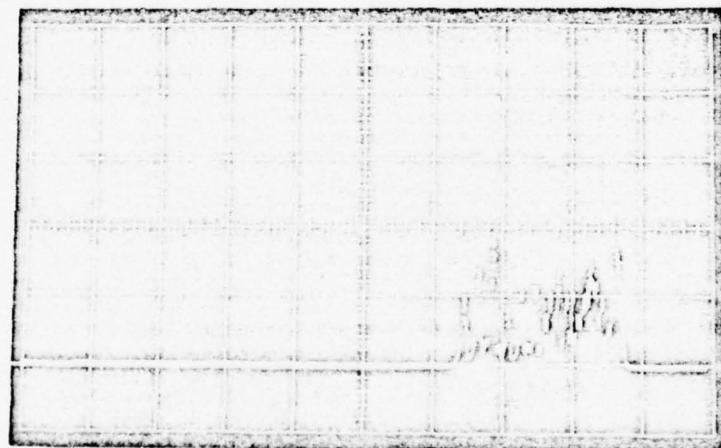
1. Viewing aperture radius in all tests was 0.95 cm.
2. Distance between pyrotechnic pellet and detector surface was 100 cm.
3. In all tests, the pellet was positioned so that its surface was directly against the viewing aperture.
4. Ignition was accomplished in all tests with 50-4052 ignition slurry.



1 SEC/CM ←

TEST NO. 173

4 MW/CM²/CM

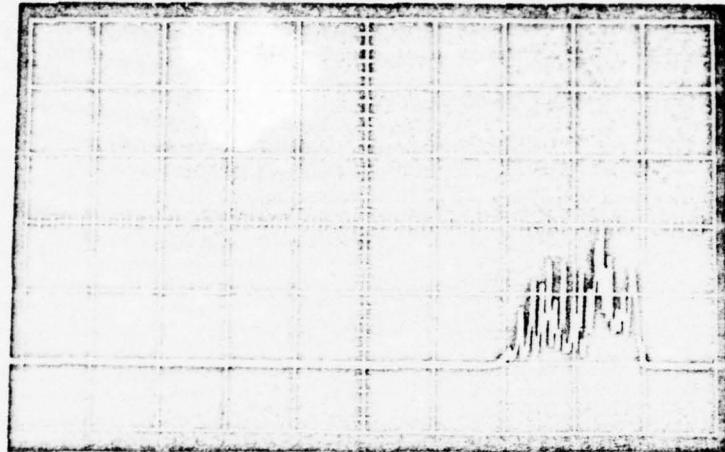


1 SEC/CM ←

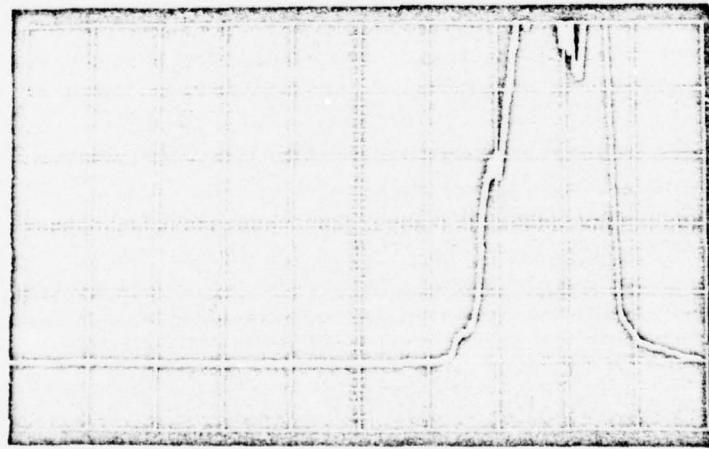
TEST NO. 174

4 MW/CM²/CM

FIGURE 5
BACK BURN FLUX/TIME TRACES

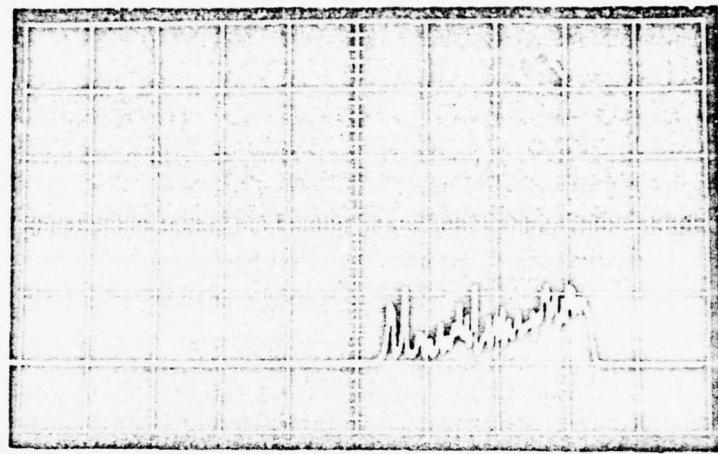


1 SEC/CM \leftarrow
TEST NO. 175

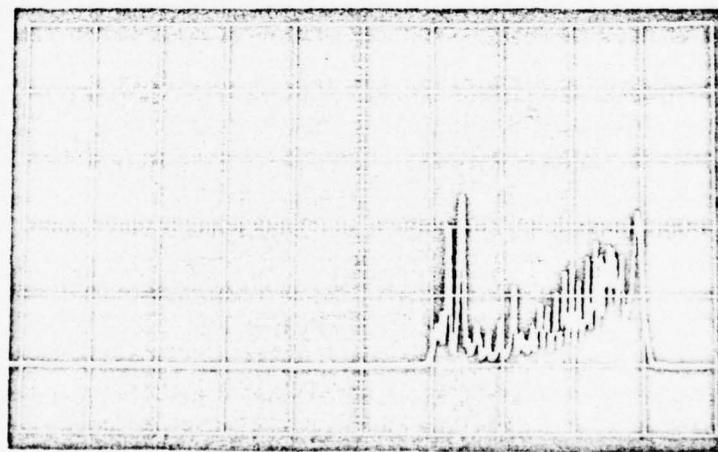


1 SEC/CM \leftarrow
TEST NO. 176

FIGURE 6
BACK BURN FLUX/TIME TRACES



TEST NO. 177



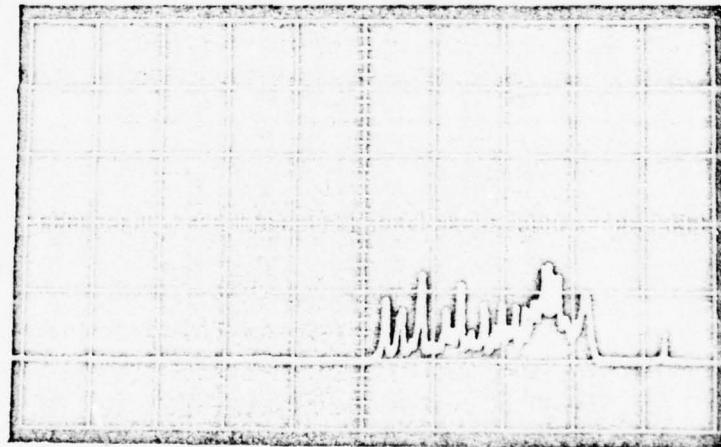
TEST NO. 178

FIGURE 7
BACK BURN FLUX/TIME TRACES



1 SEC/CM ←

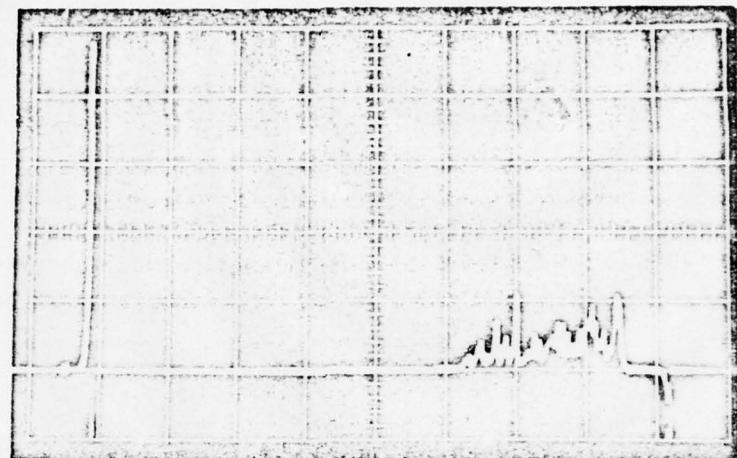
TEST NO. 179



1 SEC/CM ←

TEST NO. 180

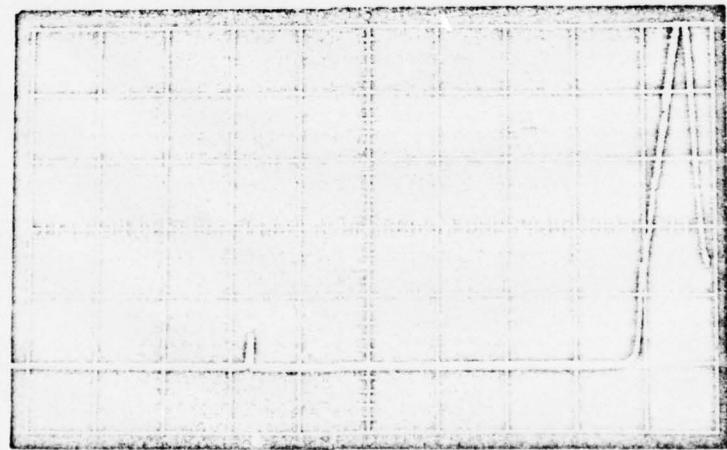
FIGURE 8
BACK BURN FLUX/TIME TRACES.



1 SEC/CM \leftarrow

TEST NO. 181

4 $\text{MW}/\text{CM}^2/\text{CM}$



1 SEC/CM \leftarrow

TEST NO. 182

4 $\text{MW}/\text{CM}^2/\text{CM}$

FIGURE 9
BACK BURN FLUX/TIME TRACES

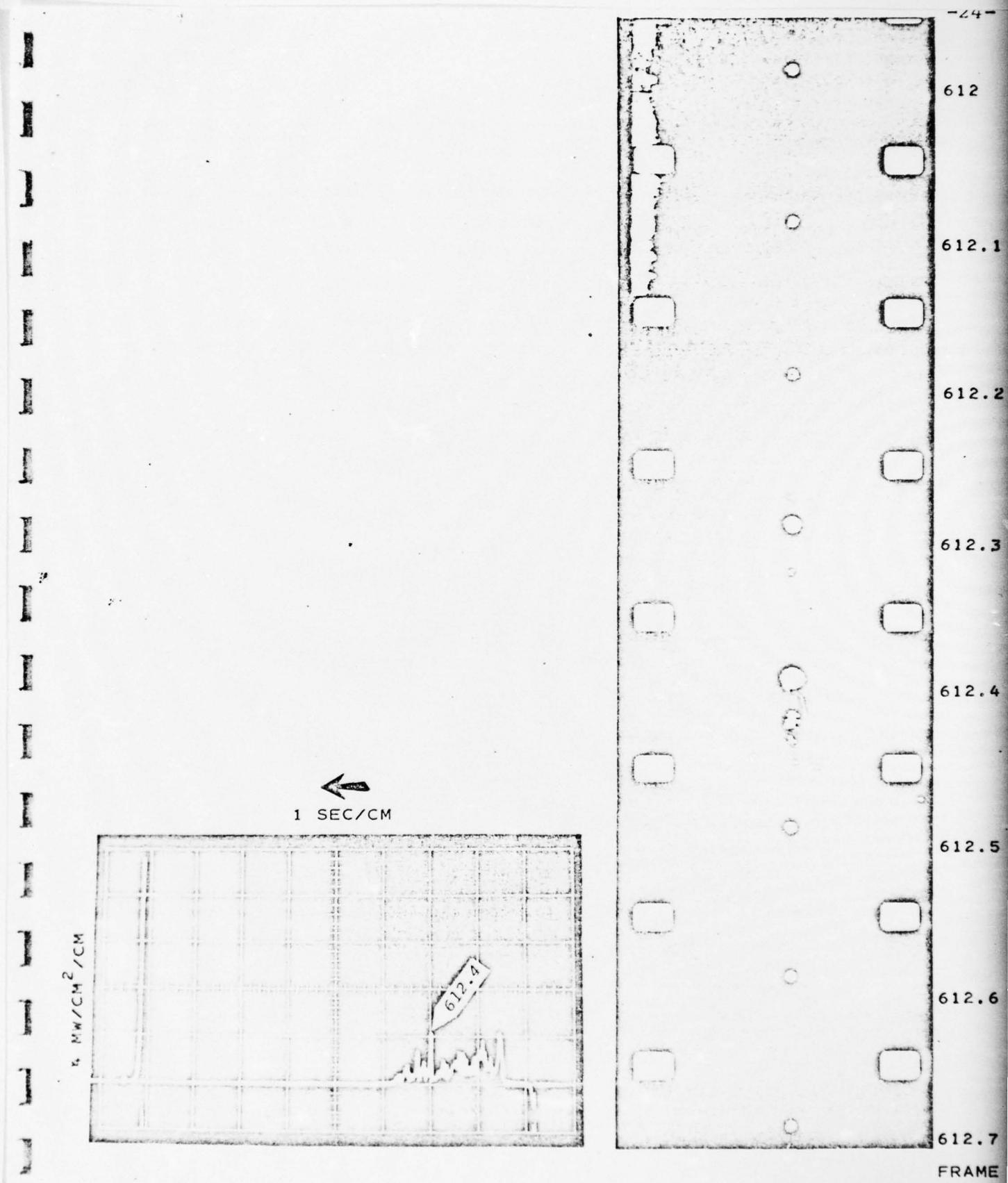


FIGURE 10
CORRELATION OF MOTION PICTURE AND OSCILLOSCOPE DATA
(TEST 181)

TASK 7 - SELECTION AND EVALUATION OF CANDIDATE PYROTECHNICS

The two pyrotechnics of primary interest as high-radiant-flux emitters were 40.0/52.5/7.5 magnesium/Halon/Fluorel (1960 Mix, Lot EL 37070) and 48/50/2 zirconium/molybdenum trioxide/Fluorel (Lot EL 37059). Both of these compositions were developed prior to the current program. Pyrotechnic research conducted during the present study consisted primarily of efforts to improve the performance and/or reduce the cost of these two formulations. In addition, at the request of HDL, a plastic-bonded photoflash composition was prepared and evaluated. A total of seven previously untested formulations was evaluated during the current program. The constituents and major combustion products of these materials are tabulated in Appendix A. For comparison, the constituents and major combustion products of 1960 Mix and EL 37059 are also listed.

Composition EL 37080 was formulated to determine the effects of using zirconium in place of one-half of the magnesium in a stoichiometric magnesium/Teflon mixture. It was anticipated that the addition of zirconium might significantly enhance the radiant output of this system without increasing its cost prohibitively. EL 37081 was prepared for the purpose of evaluating 19-micron magnesium as a replacement for one-half of the zirconium in stoichiometric zirconium/molybdenum trioxide. It was anticipated that magnesium could be substituted for a portion of the more costly zirconium in this mixture without significantly reducing its radiant output. Both EL 37080 and EL 37081 were formulated with stoichiometric O/F balances.

Based on the high radiant output of EL 37081, compositions EL 40104 and 40105 were formulated to determine the effects of varying the ratio of magnesium to zirconium over a broad range in stoichiometric magnesium/zirconium/molybdenum trioxide. These compositions were evaluated to determine the extent to which magnesium could be used as a cost-effective replacement for zirconium in the zirconium/molybdenum trioxide reaction system. Both EL 40104 and EL 40105 were formulated with stoichiometric O/F balances.

Compositions EL 40124 and EL 40125 were formulated to determine the effects on performance of adding 5 percent Fluorel binder to stoichiometric zirconium/molybdenum trioxide and 1:2 magnesium/zirconium/molybdenum trioxide, respectively. These compositions were of interest because of the very poor physical properties of the corresponding mixtures formulated with only 2 percent Fluorel (EL 37059 and EL 40104, respectively). It was anticipated that the additional Fluorel in EL 40124 and EL 40125 would enhance the pelletized physical strength of these materials without significantly reducing their radiant output levels. Both EL 40124 and EL 40125 were formulated with stoichiometric O/F balances.

At the request of HDL, Unidynamics prepared and evaluated a plastic-bonded photoflash composition. The base formulation selected for this study consisted of Type III, Class A, military photoflash powder having the following composition.

Aluminum (20 \pm 5 micron)	- 40%
Potassium Perchlorate (\sim 25 micron)	- 30%
Barium Nitrate (\sim 150 micron)	- 30%

This mixture was blended with 1 percent Fluorel binder to yield EL 37089, the formulation of which is listed in Appendix A.

The seven candidate high-radiant-flux pyrotechnics were prepared by manually blending the solid constituents into an acetone solution of Fluorel and allowing the compositions to air-dry in a fume hood with intermittent stirring and/or kneading. When completely dry, the mixtures were screened through a No. 20 sieve to break up any agglomerates and produce a uniform granulation size.

The required number of test samples of each formulation were prepared by consolidating 1.25-inch diameter pellets at a pressure of 10,000 psi and inhibiting their base and circumferential surfaces with aluminum foil-backed tape. These samples were evaluated by standardized techniques using the test setup shown in Figure 11. This setup consisted of a Hewlett-Packard 8330A/8334A meter/detector

system used in conjunction with a Honeywell Electronik 19 recorder and a Tektronix 535 oscilloscope with an H type plug-in unit. A UN-265E firing box and a UN-222C camera control for the Beattie Oscillatron/Polaroid camera assembly completed the setup.

For testing, each pellet was secured in a graphite holder and positioned so that its surface was 0.5 centimeter below and 2.0 centimeters away from the viewing aperture, which had a radius of 0.95 centimeter. The distance between the edge of the pellet and the surface of the detector was adjusted to 100 centimeters in all tests. Ignition was accomplished using one gram of 430 ignition powder (equal parts of $\text{Si}/\text{CuO}/\text{Pb}_3\text{O}_4$) lightly tamped on the surface of the pellet and an M-100 electric match suspended above the 430. The electric match was fired by a five-ampere current from the UN-265E. The recorder and oscilloscope were activated just prior to ignition.

Burn rate and radiant flux values obtained for the seven experimental formulations are listed in Table V. In addition, this table includes the radiant output data obtained for EL 40130. This composition was prepared late in the program to replace the depleted supply of EL 37059 and was identical to that material in formulation. For comparison, the output values obtained for four groups of 1960 control pellets tested at different times during the program are also listed in Table V.

As will be seen in Table V, the calculated irradiance of EL 37080 ($38.3 \text{ cal/cm}^2/\text{sec}$) averaged approximately 20 percent less than that of its parent composition, 1960 Mix ($46.1 \text{ cal/cm}^2/\text{sec}$ in tests conducted at the same time). In addition, the 18-micron zirconium used in EL 37080 is potentially far more expensive than the Granulation 16 magnesium which it replaces in 1960 Mix. For these reasons, the evaluation of EL 37080 was discontinued after the initial test series. The maximum calculated irradiance of EL 37081 averaged $69.5 \text{ cal/cm}^2/\text{sec}$ in all tests and $73.3 \text{ cal/cm}^2/\text{sec}$ if the low value from Test No. 160 is excluded. By comparison,

the maximum radiant flux of EL 37059 (48/50/2 zirconium/molybdenum trioxide/Fluorel) averaged $88.4 \text{ cal/cm}^2/\text{sec}$ in initial tests conducted during the previous program and typically exceeded $80 \text{ cal/cm}^2/\text{sec}$ throughout its evaluation. Thus, the maximum calculated irradiance of EL 37081 was approximately 20 percent less than that of its zirconium-based parent composition. However, the cost of EL 37081 should be approximately 30 percent less than that of the all-zirconium formulation. For this reason, the use of EL 37081 or a similar composition appeared promising as a means of increasing the cost effectiveness of the zirconium/molybdenum trioxide system. Accordingly, investigations were continued in this area to determine the extent to which magnesium could be substituted for zirconium without significantly reducing radiant output. The compositions prepared in this study were EL 40104 (1:2 magnesium/zirconium molar ratio) and EL 40105 (2:1 magnesium/zirconium molar ratio).

As shown in Table V, the maximum calculated irradiance of EL 40104 (1:2 magnesium/zirconium) averaged approximately $82 \text{ cal/cm}^2/\text{sec}$ if the results of Test No. 191 are excluded. This compares very favorably with the average maximum irradiance of the all-zirconium parent composition, EL 37059 ($80 \text{ cal/cm}^2/\text{sec}$ or greater in most tests). Additionally, because of its lower zirconium content, the cost of EL 40104 should be considerably less than that of EL 37059. EL 40104 differs from EL 37059 principally in its much faster burn rate ($\sim 0.7 \text{ in/sec}$ for EL 40104 compared to $\sim 0.1 \text{ in/sec}$ for EL 37059). Thus, EL 40104 appears very promising as a high-radiant-output pyrotechnic for applications requiring fast-burning, peak-type flux-time signatures. By comparison, the average maximum radiant flux of EL 40105 (2:1 magnesium/zirconium) was found to be considerably below that of EL 37059, and its evaluation was discontinued.

As seen in Table V, the maximum calculated irradiance of EL 40124 (stoichiometric zirconium/molybdenum trioxide with 5 percent

Fluorel) and EL 40125 (1:2 magnesium/zirconium/molybdenum trioxide with 5 percent Fluorel) averaged only $31.3 \text{ cal/cm}^2/\text{sec}$ and $45.8 \text{ cal/cm}^2/\text{sec}$, respectively. Both of these compositions yielded radiant outputs far below anticipated levels. Also, inexplicably, the all-zirconium formulation generated a radiant flux level significantly below that of the magnesium-modified mixture. One explanation for the low radiant outputs of EL 40124 and EL 40125 could be the relatively slow burn rates of these materials compared to those of the corresponding formulations containing only 2 percent Fluorel (EL 37059 and EL 40104, respectively). Additional research would be required to establish or disprove this relationship. However, based on data obtained during the current program, it can be concluded that neither EL 40124 or EL 40125 is especially useful in the HDL application.

Burn rate and radiant flux values obtained for the five plastic-bonded photoflash pellets are also listed in Table V. As will be seen, the peak calculated irradiance of these pellets averaged slightly less than $33 \text{ cal/cm}^2/\text{sec}$. This is significantly below the peak radiant output of 1960 Mix (40 to $50 \text{ cal/cm}^2/\text{sec}$), the material used as a minimum standard of performance. Thus, based on the results of these tests, plastic-bonded photoflash composition (EL 37089) did not appear promising as a candidate high-radiant-flux pyrotechnic, and its evaluation was not pursued.

The final series of laboratory irradiance tests during the current program was performed to establish the radiant output of a new lot of stoichiometric zirconium/molybdenum trioxide (EL 40130). This composition was prepared late in the program to replace the depleted supply of EL 37059. As will be seen in Table V, the irradiance values obtained for EL 40130 were somewhat inconsistent. Even if the low value from Test No. 209 is disregarded, the maximum calculated irradiance of EL 40130 ranged from 55.6 to $82.1 \text{ cal/cm}^2/\text{sec}$ and averaged only $72 \text{ cal/cm}^2/\text{sec}$. This average represents a radiant output level 10 to 20 percent below that typically obtained for EL 37059. However, the $82.1 \text{ cal/cm}^2/\text{sec}$ value confirmed the potential of EL 40130 as a high flux emitter, and the material was accepted for use in the second series of large array tests.

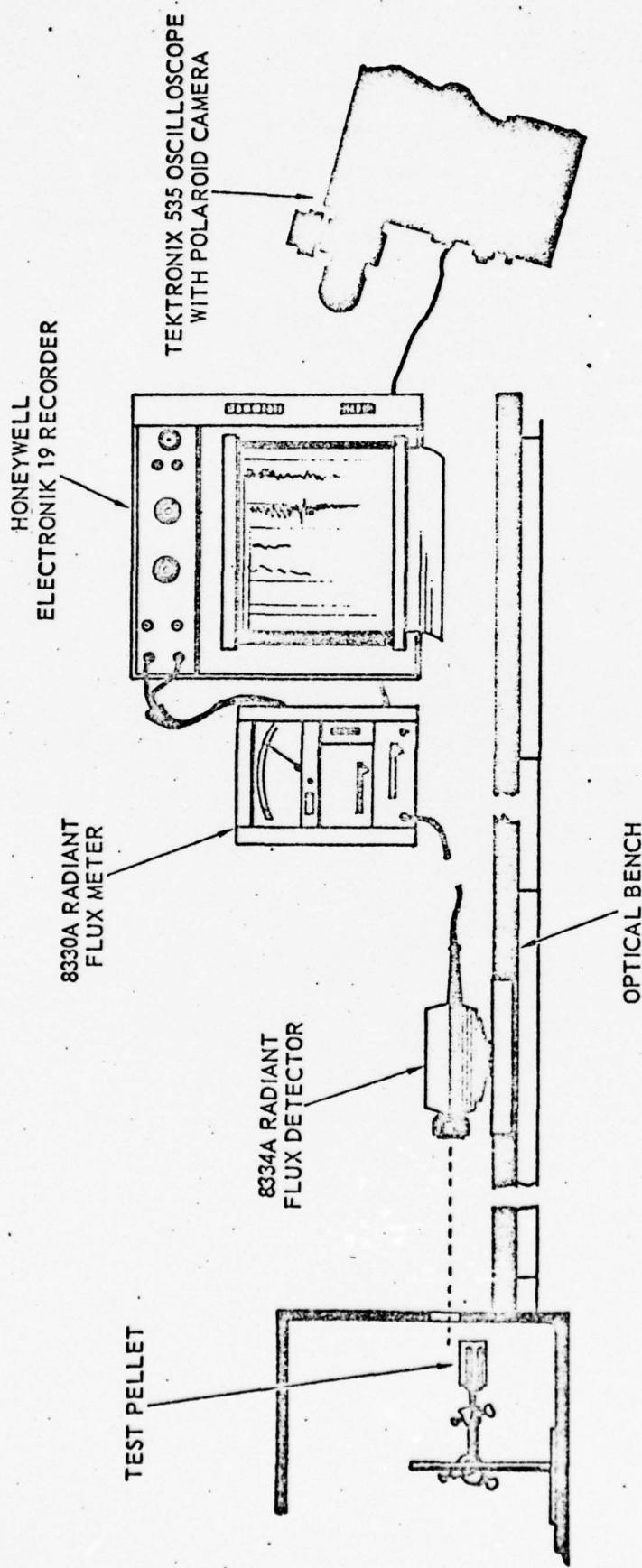


FIGURE 11
RADIANT FLUX TEST SETUP

TABLE V
PELLET PROPERTIES AND RADIANT EMITTANCE DATA
FOR CANDIDATE PYROTECHNICS

Test No. (S/N)	Composition	Pellet Weight (gm)	Pellet Thickness (in)	Pellet Density (gm/cm ³)	Pellet Burn Rate (in/sec)	Maximum Measured Irradiance (mw/cm ²)	Maximum Calculated Source Irradiance (cal/cm ² /sec)	Remarks
155	Mg/Zr/Teflon/Fluorol Lot EL 37080	17.16	0.364	2.34	0.02	13.8	36.5	Fairly consistent trace
156	Mg/Zr/Teflon/Fluorol Lot EL 37080	17.05	0.263	2.34	0.02	15.0	39.7	Somewhat erratic trace
157	Mg/Zr/Teflon/Fluorol Lot EL 37080	17.23	0.371	2.33	0.02	15.6	41.3	Very consistent trace
158	Mg/Zr/Teflon/Fluorol Lot EL 37080	17.23	0.366	2.34	0.02	13.5	35.7	Fairly consistent trace
159	Mg/Zr/WO ₃ Fluorol Lot EL 37081	22.01	0.274	2.93	0.37	27.0	71.5	Peak type trace, rapid burn
160	Mg/Zr/WO ₃ Fluorol Lot EL 37081	21.83	0.403	2.70	0.67	22.0	58.2	Peak type trace, rapid burn
161	Mg/Zr/WO ₃ Fluorol Lot EL 37081	22.13	0.408	2.70	0.58	29.0	76.8	Peak type trace, rapid burn
162	Mg/Zr/WO ₃ Fluorol Lot EL 37081	21.91	0.403	2.70	0.67	27.0	71.5	Peak type trace, rapid burn
163	Al/KClO ₄ /Ba(NO ₃) ₂ /Fluorol Lot EL 37083	15.23	0.335	2.27	0.03	14.0	37.1	Fairly consistent trace
164	Al/KClO ₄ /Ba(NO ₃) ₂ /Fluorol Lot EL 37083	15.16	0.332	2.27	0.03	13.8	36.5	Very consistent trace
165	Al/KClO ₄ /Ba(NO ₃) ₂ /Fluorol Lot EL 37083	15.27	0.338	2.25	0.03	10.8	28.6	Fairly consistent trace
166	Al/KClO ₄ /Ba(NO ₃) ₂ /Fluorol Lot EL 37083	15.21	0.337	2.25	0.03	14.4	38.1	Fairly consistent trace
167	Al/KClO ₄ /Ba(NO ₃) ₂ /Fluorol Lot EL 37083	15.30	0.336	2.27	0.03	9.9	23.8	Fairly consistent trace
170	Mg/Halon/Fluorol Lot EL 37070 (1960 Mix)	15.24	0.387	1.96	0.03	16.8	44.5	Very consistent trace
171	Mg/Halon/Fluorol Lot EL 37070 (1960 Mix)	15.21	0.389	1.94	0.03	16.2	42.9	Very consistent trace
172	Mg/Halon/Fluorol Lot EL 37070 (1960 Mix)	15.17	0.385	1.96	0.03	19.2	50.8	Very consistent trace
185	Mg/Halon/Fluorol Lot EL 37070 (1960 Mix)	15.08	0.390	1.92	0.03	17.1	45.3	Fairly consistent trace
186	Mg/Halon/Fluorol Lot EL 37070 (1960 Mix)	15.10	0.391	1.92	0.03	17.0	45.0	Fairly consistent trace
187	Mg/Halon/Fluorol Lot EL 37070 (1960 Mix)	15.06	0.390	1.92	0.03	16.1	42.6	Fairly consistent trace
189	Mg/Zr/WO ₃ /Fluorol Lot EL 40104	19.95	0.346	2.67	0.69	30.8	81.5	Peak type trace, rapid burn
190	Mg/Zr/WO ₃ /Fluorol Lot EL 40104	20.00	0.351	2.83	0.70	31.0	82.1	Peak type trace, rapid burn
191	Mg/Zr/WO ₃ /Fluorol Lot EL 40104	19.94	0.344	2.83	0.69	21.5	56.9	Peak type trace, rapid burn
192	Mg/Zr/WO ₃ /Fluorol Lot EL 40105	19.84	0.397	2.49	0.79	24.0	63.5	Peak type trace, rapid burn
193	Mg/Zr/WO ₃ /Fluorol Lot EL 40105	20.07	0.403	2.48	0.81	22.3	59.0	Peak type trace, rapid burn
194	Mg/Zr/WO ₃ /Fluorol Lot EL 40105	20.00	0.398	2.51	0.80	23.4	61.9	Peak type trace, rapid burn
195	Zr/WO ₃ /Fluorol Lot EL 40124	23.30	0.269	4.00	0.07	12.1	32.0	Very consistent trace
196	Zr/WO ₃ /Fluorol Lot EL 40124	23.27	0.290	3.98	0.07	11.2	29.7	Fairly consistent trace
197	Zr/WO ₃ /Fluorol Lot EL 40124	23.44	0.291	3.96	0.07	12.6	33.4	Fairly consistent trace
198	Zr/WO ₃ /Fluorol Lot EL 40124	23.44	0.292	3.98	0.07	11.4	30.2	Fairly consistent trace

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TABLE V (CONTINUED)
PELLET PROPERTIES AND RADIANT EMITTANCE DATA
FOR CANDIDATE PYROTECHNICS

Test No. (S/N)	Composition	Pellet Weight (gm)	Pellet Thickness (in)	Pellet Density (gm/cm ³)	Pellet Burn Rate (in/sec)	Maximum Measured Irradiance (mw/cm ²)	Maximum Calculated Source Irradiance (cal/cm ² /sec)	Remarks
199	Mg/2r/MgO ₃ Fluorel Lot EL 40125	23.01	0.382	2.99	0.20	18.1	47.7	Very consistent trace
200	Mg/2r/MgO ₃ Fluorel Lot EL 40125	23.01	0.382	2.99	0.18	17.4	46.1	Very consistent trace
201		23.02	0.381	3.00	0.20	17.3	45.8	Very consistent trace
202		22.94	0.380	2.99	0.20	16.5	43.7	Very consistent trace
203	Mg/Halon/Fluorel Lot EL 37070 (1560 Mix)	15.03	0.387	1.93	0.03	14.0	37.1	Very consistent trace
204		15.04	0.387	1.93	0.03	16.2	42.9	Very consistent trace
205	Mg/Halon/Fluorel Lot EL 37070 (1560 Mix)	15.09	0.391	1.92	0.03	15.6	41.3	Fairly consistent trace
206		15.03	0.395	1.94	0.03	18.6	49.2	Fairly consistent trace
207		15.06	0.386	1.94	0.03	15.6	41.3	Fairly consistent trace
208		15.15	0.391	1.92	0.03	17.4	46.1	Fairly consistent trace
209	Zr/MgO ₃ /Fluorel Lot EL 40130	23.23	0.298	3.08	0.13	16.4	43.4	Fairly consistent trace
210		23.00	0.296	3.86	0.11	29.6	78.4	Fairly consistent trace
211		23.19	0.298	3.87	0.10	21.0	55.6	Fairly consistent trace
212		23.66	0.301	3.91	0.10	31.0	82.1	Fairly consistent trace

Notes:

1. Viewing aperture radius in all tests was 0.95 cm.
2. Distance between Pyrotechnic Pellet and detector surface was 100 cm.
3. In all tests, the pellet was positioned so that its surface was 0.5 cm below and 2.0 cm away from the viewing aperture.
4. Ignition was accomplished in all tests with 430 ignition powder and an M-100 electric match.
5. During Test No.'s 191 and 209, the plumes were inadvertently canted away from the aperture.

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TASK 8 - TESTING OF LARGE PYROTECHNIC ARRAYS

Two series of large pyrotechnic arrays (nine tests total) were assembled and burned in the light tunnel during the current program. Each array contained three (Series 1) or four (Series 2) transite panels with pyrotechnic pellets bonded to one side. The panels were 2 inches wide by 9 inches long and held either two or four rectangular pellets aligned end to end and secured in place with epoxy resin. Each pellet contained a surface layer of compressed titanium/boron/Fluorel as an ignition aid. The ignition surface of each pellet was painted with a thin coating of nitro-cellulose lacquer and allowed to dry. A length of 0.125-inch diameter extruded 50-4052 pyrotechnic cord was then secured to the top surface of the pellet assembly using a strip of aluminum foil-backed tape. As in the ignition aid studies, the tape was applied in a manner which held the cord firmly in place against the pellet surfaces while leaving a space on each side to cause a rapid flash to propagate along the length of the assembly upon ignition. The exposed ends of the ignition cords in each array were ignited simultaneously by means of individual M-100 electric matches and small packets of 430 ignition powder.

For testing in the light tunnel, each array in Series 1 was positioned approximately 1 inch away from a 1.25-inch radius viewing aperture (4.9 square inches) in the closed end of the tunnel. The three panels comprising the array were oriented at right angles to the aperture and secured in place with a wire harness. A smoke removal fan with 20-inch blades located approximately 1 foot behind the array was operated during each test to draw smoke away from the aperture. Radiant flux and total burn time were determined by means of the Hewlett-Packard 8330A/8334A meter/detector system used in conjunction with a Tektronix 535 oscilloscope. The distance between the pyrotechnic array and the surface of the detector was 5.7 meters in the Series 1 tests. In addition to physical measurements, the visual effects of each test were recorded on video tape. The general configuration of the pyrotechnic arrays

in the Series 1 tests is shown in Figure 12. Figure 13 illustrates the overall setup used in these tests.

The first Series 1 test (S/N 183) was conducted primarily to check the functioning of the light tunnel and auxiliary equipment. The panels used in this test each contained two pellets of 1960 Mix (Lot EL 37070) measuring 1 inch wide by 2 inches long by 0.110 inch thick. Each pellet contained a surface layer of 68/30/2 titanium/boron/Fluorel as an ignition aid. The pellets in this group were consolidated at 5,000 psi.

The second and third Series 1 tests (S/N's 184 and 185) were conducted to establish baseline irradiance values for large arrays of 1960 Mix (Lot EL 37070) and Fluorel-bonded zirconium/molybdenum trioxide (Lot EL 37059), respectively. Each panel used in these tests contained four pyrotechnic pellets measuring 1 inch wide by 1.5 inches long by 0.130 inch thick. These pellets were consolidated at 10,000 psi. Each contained a surface layer of 65/30/5 titanium/boron/Fluorel as an ignition aid.

Pellet parameters and data obtained in the three Series 1 tests are presented in Table VI. As will be seen, the two tests of 1960 Mix yielded very consistent maximum calculated irradiance values. However, the average of these values ($36.1 \text{ cal/cm}^2/\text{sec}$) was approximately 20 percent below that typically obtained for 1960 Mix in small-scale laboratory testing. By comparison, the maximum calculated irradiance of Fluorel-bonded zirconium/molybdenum trioxide ($108.3 \text{ cal/cm}^2/\text{sec}$) was 20 to 30 percent greater than that obtained during laboratory testing of this material.

Based on the results of the Series 1 tests, it was concluded that the use of large pyrotechnic arrays to produce high levels of radiant flux was feasible, and a second series of tests was performed.

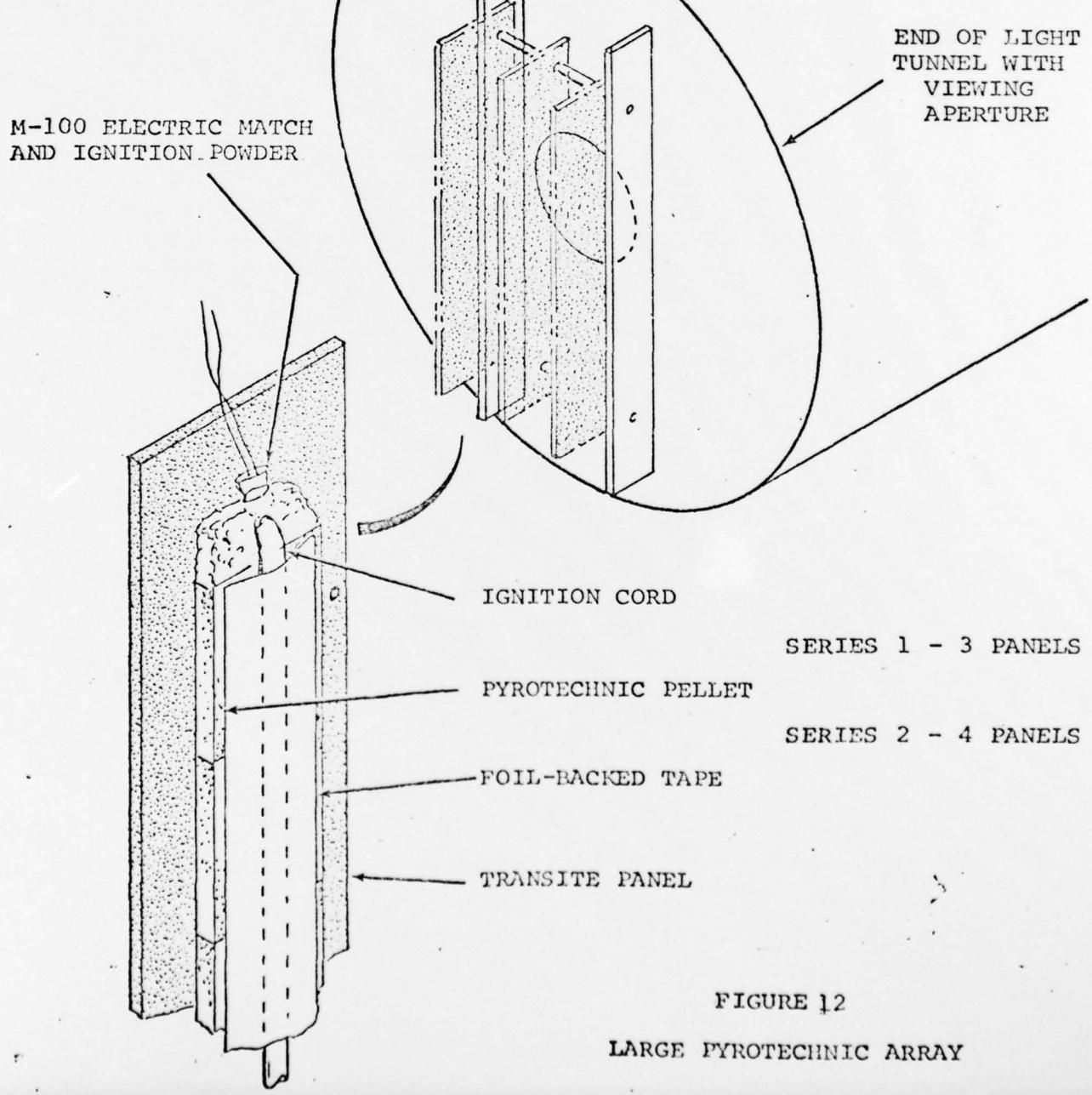
For testing in the light tunnel, each array in Series 2 was positioned approximately 1 inch away from a 3.00-inch radius viewing aperture (28.3 square inches) in the closed end of the tunnel. The four panels comprising the array were oriented at right angles to the aperture and secured in place with a wire harness. A smoke removal fan with 36-inch blades located approximately 1 foot behind the array was operated during each test to draw smoke away from the aperture. Radiant flux and total burn time were determined by means of the Hewlett-Packard 8330A/8334A meter/detector system used in conjunction with a Tektronix 535 oscilloscope. The distance between the pyrotechnic array and the surface of the detector was 5.7 meters in the Series 2 tests. In addition to physical measurements, the visual effects of each test were recorded on video tape, color motion pictures, and black-and-white still photographs. The general configuration of the pyrotechnic arrays in the Series 2 tests is shown in Figure 12. Figure 13 illustrates the overall setup used in these tests.

The six Series 2 tests (S/N's 213 through 218) were conducted to determine the irradiance levels of large arrays of 1960 Mix (Lot EL 37070) and Fluorel-bonded zirconium/molybdenum trioxide (Lot EL 40130). Each panel used in these tests contained four pyrotechnic pellets measuring 1 inch wide by 1.5 inches long by ~ 0.110 inch thick. These pellets were consolidated at 10,000 psi. Each pellet contained a copressed surface layer of 65/30/5 titanium/boron/Fluorel as an ignition aid.

Pellet parameters and data obtained in the six Series 2 tests are listed in Table VII. As will be seen, the maximum irradiance values obtained for both materials varied considerably (22.2 to 63.8 $\text{cal/cm}^2/\text{sec}$ for 1960 Mix and 32.3 to 65.9 $\text{cal/cm}^2/\text{sec}$ for EL 40130). Using these values, the average maximum outputs were 45.2 and 51.1 $\text{cal/cm}^2/\text{sec}$ for 1960 Mix and EL 40130, respectively. If the plateau irradiance values are compared, the variation is 16.1 to 32.9 $\text{cal/cm}^2/\text{sec}$ for 1960 Mix and 32.3 to 55.1 $\text{cal/cm}^2/\text{sec}$ for EL 40130. The average maximum flux levels then become 25.7

and 45.7 cal/cm²/sec for 1960 Mix and EL 40130, respectively. Test No.'s 217 and 218 yielded significantly lower radiant output levels than the four preceding tests. If the results of these tests are excluded, the average maximum/plateau irradiance levels become 56.8/30.6 and 60.5/52.4 cal/cm²/sec for 1960 Mix and EL 40130, respectively. Regardless of which set of values is compared, it is apparent that the radiant output levels achieved in the Series 2 tests were somewhat lower than those from the Series 1 tests. However, many factors were different in the two series of tests, including aperture size, pyrotechnic burning area, pellet thicknesses and total burn times, exhaust fan size, ambient environmental conditions, etc. For these reasons, far more extensive testing would be required to establish the true potential of 1960 Mix, Fluorel-bonded stoichiometric zirconium/molybdenum trioxide, or any other pyrotechnic as a radiant emitter in very large arrays. However, based on the results of tests conducted to date, it can be concluded that the application of large pyrotechnic arrays as radiant flux generators is definitely feasible.

It should be noted the initial maximum values with Series 2 testing may be due to a large extent to the Ti/B ignition composition. Fairly high irradiance peaks were also noted with the Series 1 tests. Indeed it may be appropriate to further investigate Ti/B compositions when short radiant pulses of moderate to upper level are required, e.g., superimposition of Ti/B emission on 1960 output to arrive at a decay type irradiance curve.



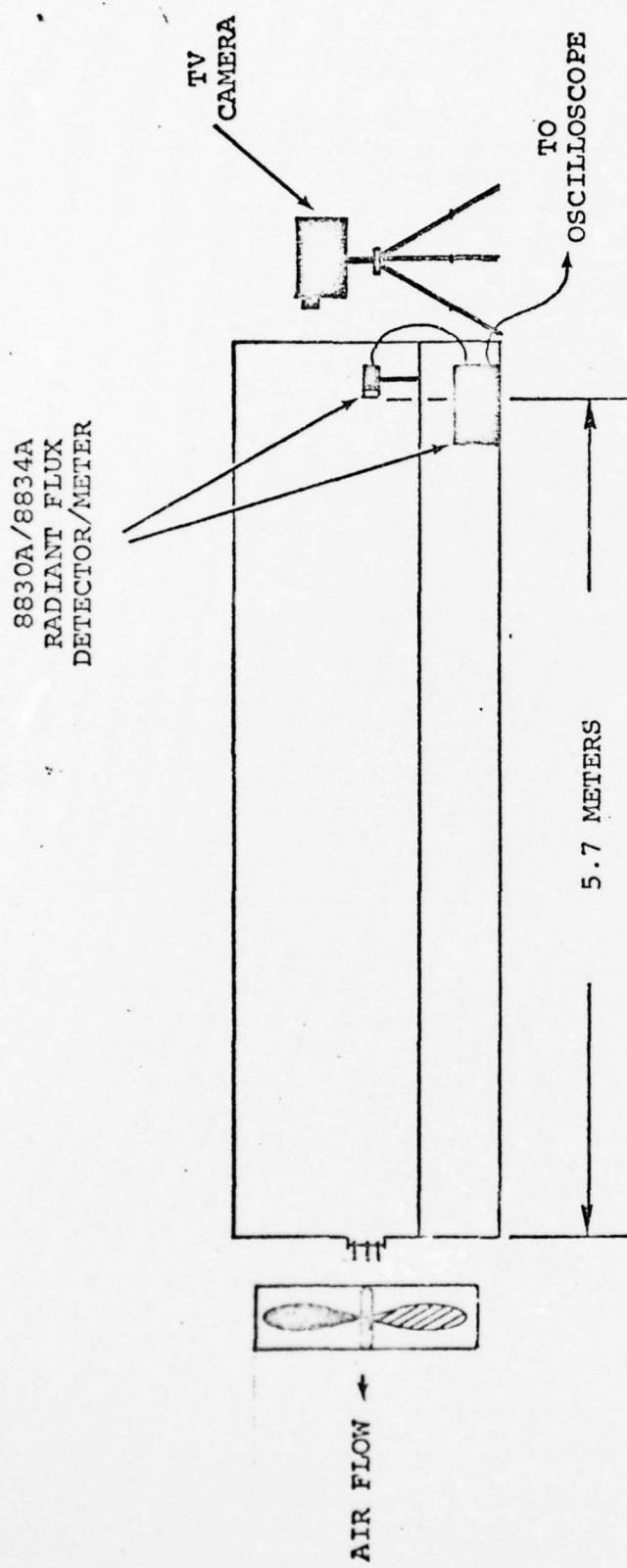


FIGURE 1.3
LARGE ARRAY TEST SETUP

TABLE VI
LARGE ARRAY TESTS
(SERIES 1)

Test No. (S/N)	Pellet Base Material/ Weight	Pellet Ignition Material/ Weight	Overall Dimensions of Individual Pellet Array (in)	Total Array Burn Time (sec)	Maximum Measured Irradiance (mw/cm ²)	Maximum Calculated Source Irradiance (cal/cm ² /sec)
183	1960 Mix/ 5 grams	EL 40106/ 1 gram	1 x 4 x 0.110	~3	4.8	36.9
184	1960 Mix/ 5 grams	EL 40113/ 1 gram	1 x 6 x 0.130	~3	4.6	35.3
185	EL 37059/ 10 grams	EL 40113/ 1 gram	1 x 6 x 0.130	~1.5	14.1	108.3

Notes:

1. Viewing aperture radius in all tests was 1.25 inches (3.18 cm).
2. Distance between pyrotechnic array and detector surface was 5.7 meters.

TABLE VII
LARGE ARRAY TESTS
(SERIES 2)

Test No. (S/N)	Pellet Base Material/Weight	Pellet Ignition Material/Weight	Total Array Burn Time (sec)	Maximum Measured Irradiance (mw/cm ²)	Maximum Calculated Source Irradiance (cal/cm ² /sec)
213	1960 Mix/ 5 grams	EL 40113/ 0.5 gram	3.3	37.0 ⁽¹⁾	49.7 ⁽¹⁾
214	EL 40130/ 9 grams	EL 40113/ 0.5 gram	1.1	49.0 ⁽²⁾	65.9 ⁽²⁾
215	1960 Mix/ 5 grams	EL 40113/ 0.5 gram	3.7	47.5 ⁽³⁾	63.8 ⁽³⁾
216	EL 40130/ 9 grams	EL 40113/ 0.5 gram	1.3	41.0	55.1
217	1960 Mix/ 5 grams	EL 40113/ 0.5 gram	3.2	16.5 ⁽⁴⁾	22.2 ⁽⁴⁾
218	EL 40130/ 9 grams	EL 40113/ 0.5 gram	1.2	24.0	32.3

Notes:

- (1) Maximum level on ignition; plateau level was 28.2 cal/cm²/sec.
- (2) Maximum level on ignition; plateau level was 49.7 cal/cm²/sec.
- (3) Maximum level on ignition; plateau level was 32.9 cal/cm²/sec.
- (4) Maximum level on ignition; plateau level was 16.1 cal/cm²/sec.

CONCLUSIONS AND RECOMMENDATIONS

Based on the data collected during both the current program and the previous study, the following major conclusions can be formed.

1. Of all the formulations evaluated during both programs, the material yielding the highest irradiance is 41/10/47/2 zirconium/thorium/molybdenum trioxide/Fluorel. This composition is capable of generating radiant flux levels in excess of $100 \text{ cal/cm}^2/\text{sec}$. However, the material is considered impractical and unsafe to use because of the radioactivity of thorium; and its further evaluation is not recommended.
2. Of all the formulations evaluated during both programs, the material yielding the second highest irradiance is 48/50/2 zirconium/molybdenum trioxide/Fluorel. This composition is capable of generating radiant flux levels in excess of $80 \text{ cal/cm}^2/\text{sec}$. This material is practical and relatively safe to use, and its evaluation should be continued. In order to improve its pelletized physical properties, it is recommended that the material be consolidated at very high pressures, i.e. 30,000 to 50,000 psi. In addition, it is recommended that the formulation be modified by the incorporation of additional Fluorel binder, i.e., 2 to 4 percent.
3. Of all the formulations evaluated during both programs, the material yielding the most consistent, moderately high radiant output is 40/52.5/7.5 magnesium/Halon/Fluorel (Unidynamics' 1960 Mix). This composition is relatively inexpensive and relatively safe to use and has excellent pelletized physical properties. All constituents for this material are readily available. Further evaluation of this formulation and minor modifications thereof is strongly recommended due to the practicality of the system.

4. The smoke from burning pellets of 40/52.5/7.5 magnesium/Halon/Fluorel (1960 Mix) is not excessive under atmospheric conditions, and its dispersal should not be a serious problem. By comparison, the smoke from burning pellets of 48/50/2 zirconium/molybdenum trioxide/Fluorel or related formulations is very dense, and its dispersal could be a very serious problem.
5. Effective ignition aids for use with any high-radiant-flux formulation of interest have been developed. The ignition aid components consist of layers of fast-burning pyrotechnic copressed into the pellet surfaces combined with high-rate pyrotechnic flash cords extended across the pellet surfaces.
6. The use of an exhaust fan is a feasible method for dispersing the smoke from properly configured large pyrotechnic arrays. However, this method would not be effective for all types of large arrays.
7. The backburn pellet combustion mode is not an effective means of achieving short-duration, high-intensity radiant bursts. Other potentially more effective methods include the use of pellets containing various types of concave surface indentations.
8. Graphite panels should be employed in the construction of large pyrotechnic arrays to avoid the problems associated with thermal spalling of transite or other hydrous construction materials.

APPENDIX A
PYROTECHNIC FORMULATIONS

CANDIDATE HIGH-RADIANT-FLUX PYROTECHNICS

Composition	Ingredient Ratio	Major Combustion Products
EL 37059 and EL 40130	Zirconium (18 micron) - 48.0% Molybdenum Trioxide (City Chemical) - 50.0% Fluorel KF 2140 - 2.0%	ZrO ₂ Mo *
EL 37070 (1960 Mix)	Magnesium (200/325 mesh) - 40.0% Halon G-80 - 52.5% Fluorel KF 2140 - 7.5%	MgF ₂ C *
EL 37080	Magnesium (200/325 mesh) - 19.0% Zirconium (18 micron) - 19.0% Teflon 7A - 60.0% Fluorel KF 2140 - 2.0%	MgF ₂ ZrF ₄ C *
EL 37081	Magnesium (19 micron) - 19.0% Zirconium (18 micron) - 19.0% Molybdenum Trioxide (City Chemical) - 60.0% Fluorel KF 2140 - 2.0%	MgO ZrO ₂ Mo *
EL 40104	Magnesium (19 micron) - 16.0% Zirconium (18 micron) - 24.0% Molybdenum Trioxide (City Chemical) - 58.0% Fluorel KF 2140 - 2.0%	MgO ZrO ₂ Mo *
EL 40105	Magnesium (19 micron) - 24.0% Zirconium (18 micron) - 14.0% Molybdenum Trioxide (City Chemical) - 60.0% Fluorel KF 2140 - 2.0%	MgO ZrO ₂ Mo *
EL 40124	Zirconium (18 micron) - 47.0% Molybdenum Trioxide (City Chemical) - 48.0% Fluorel KF 2140 - 5.0%	ZrO ₂ Mo *
EL 40125	Magnesium (19 micron) - 15.0% Zirconium (18 micron) - 24.0% Molybdenum Trioxide (City Chemical) - 56.0% Fluorel KF 2140 - 5.0%	MgO ZrO ₂ Mo *
EL 37039 (Plastic-bonded Photoflash)	Aluminum (20 micron) - 39.6% Potassium Perchlorate (35 micron) - 29.7% Barium Nitrate (200 micron) - 29.7% Fluorel KF 2140 - 1.0%	Al ₂ O ₃ KCl BaO N ₂ *

*Excluding the combustion products from the Fluorel binder.

APPENDIX B
COMPARATIVE SUMMARY OF
TESTING TEST DATA

COMPARATIVE SUMMARY OF PELLET TEST DATA

The data traces from all tests performed during both the current program and the previous study were reviewed, and all useful compositions were arranged in two groups in decreasing order of effectiveness as radiant emitters. This comparative summary of data is contained in the tables at the conclusion of this appendix.

From the data summary, it is apparent that the compositions which yielded the highest radiant flux levels were all of the metal/metal oxide type. Specifically, the best composition in this respect was 41/10/47/2 zirconium/thorium/molybdenum trioxide/Fluorel. Based on four tests, the maximum calculated irradiance of this material averaged 105.9 cal/cm²/sec. However, this composition is not usable in the HDL application because of its thorium content, which is regarded as a serious health hazard due to its radioactivity. The second-ranked formulation with respect to maximum calculated irradiance was 48/50/2 zirconium/molybdenum trioxide/Fluorel. This material emitted an average maximum of 88.4 cal/cm²/sec in initial tests during the first program and typically yielded irradiance values in excess of 80 cal/cm²/sec throughout both programs. Although its performance was somewhat erratic during large array testing, this formulation is considered the optimum pyrotechnic system developed during both programs.

Other metal/metal oxide formulations which yielded high radiant flux levels included 16/24/58/2 and 19/19/60/2 magnesium/zirconium/molybdenum trioxide/Fluorel (\sim 80 and \sim 70 cal/cm²/sec, respectively), 64/34/2 hafnium/molybdenum trioxide/Fluorel (\sim 80 cal/cm²/sec), and 36/62/2 zirconium/tungsten trioxide/Fluorel (variable but capable of reaching \sim 65 cal/cm²/sec). The first two mixtures are considered very promising for the HDL application, especially where short-duration, high-intensity radiant pulses are required. However, the third composition is impractical due to the excessive cost of hafnium; and the last material has yielded inconsistent radiant output.

None of the other metal/metal oxide formulations evaluated during either program appear promising for the HDL application.

From the standpoint of radiant output, the second-ranking class of pyrotechnics evaluated was the metal/polyfluorocarbon system. Useful formulations of this type all consisted of magnesium/polytetrafluoroethylene (Teflon 7A or Halon G-80) mixtures incorporating Fluorel as an auxiliary binder. The most effective radiant emitter among the metal/polyfluorocarbon mixtures evaluated was 40/52.2/7.5 magnesium/Halon/Fluorel. This near-stoichiometric formulation, which is designated 1960 Mix, has been used by Unidynamics on numerous occasions as a pyrotechnic ignition material. In 24 tests, this mixture yielded an average maximum calculated irradiance of 46.1 cal/cm²/sec and demonstrated a high degree of consistency.

None of the other metal/polyfluorocarbon compositions evaluated appear to offer any significant advantage over 1960 Mix.

Formulation types which were evaluated and shown to offer little or no promise for use in the HDL application include metal/perchlorate, metal/sulfate, and metal/nitrate.

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CANDIDATE PYROTECHNICS IN DECREASING ORDER OF
EFFECTIVENESS AS RADIANT EMITTERS

Test No. (S N)	Composition	Pellet Weight (gm)	Pellet Thickness (in)	Pellet Density (gm/cm ³)	Pellet Burn Rate (in/sec)	Maximum Measured Irradiance (mw/cm ²)	Maximum Calculated Source Irradiance (cal/cm ² /sec)	Remarks
149	Zr Th Mo ₃ Fluorel Lot EL 37052	22.82	0.276	4.11	0.18	41.5	109.9	Very consistent trace
150		22.82	0.277	4.10	0.18	37.5	99.3	Fairly consistent trace
151		22.91	0.279	4.10	0.18	41.5	109.9	Fairly consistent trace
152		22.72	0.276	4.09	0.18	39.5	104.6	Very consistent trace
25	Zr Mo ₃ Fluorel Lot EL 37012	23.42	0.291	3.98	0.14	24.5	64.9	Fairly consistent trace
26		23.45	0.299	3.88	0.14	36.0	95.3	Fairly consistent trace
27		23.48	0.292	3.96	0.14	38.0	100.6	Very consistent trace
46		18.38	0.235	3.86	0.13	35.0	92.6	Very consistent trace
95	Zr Mo ₃ Fluorel (1% Fluorel) Lot EL 37038	24.77	0.322	3.79	0.13	37.2	98.5	Fairly consistent trace
96		24.80	0.322	3.80	0.13	33.0	87.4	Somewhat erratic trace
132	Zr Mo ₃ Fluorel (Fine Zr) Lot EL 37054	9.25	0.137	3.33	0.43	34.0	90.0	Short peak type trace
133		9.29	0.135	3.39	0.41	34.0	90.0	Short peak type trace
141	Zr Mo ₃ Fluorel Lot EL 37059	24.86	0.315	3.92	0.14	31.5	83.4	Fairly consistent trace
142		24.67	0.314	3.91	0.13	33.0	87.4	Fairly consistent trace
143		24.86	0.313	3.95	0.13	31.5	83.4	Fairly consistent trace
144		25.13	0.317	3.94	0.14	32.0	84.7	Very consistent trace
153	Hf Mo ₃ Fluorel Lot EL 37060	23.54	0.220	5.32	0.22	28.5	75.4	Peak type trace
154		23.70	0.222	5.31	0.24	32.5	86.0	Peak type trace
61	Zr Mo ₃ Fluorel (Sieved Mo ₃)	24.83	0.317	3.86	0.13	33.2	87.9	Fairly consistent trace
62		24.76	0.317	3.85	0.14	23.6	62.5	Somewhat erratic trace
63		24.85	0.317	3.86	0.13	24.8	65.6	Very consistent trace
64		24.88	0.318	3.85	0.14	33.0	87.4	Erratic trace
59	Zr Mo ₃ Fluorel (Unsieved Mo ₃) Lot EL 37033	24.96	0.329	3.74	0.14	13.6	81.0	Fairly consistent trace
110	Zr Mo ₃ Fluorel (Fuel-rich) Lot EL 37043	24.81	0.300	4.07	0.21	23.8	63.0	Fairly consistent trace
111		24.94	0.302	4.07	0.23	28.6	75.7	Fairly consistent trace
93	Zr Mo ₃ Fluorel (Fine Zr) Lot EL 37037	24.68	0.263	4.62	0.11	21.0	55.6	Peak type trace
116		24.18	0.257	4.64	0.10	24.3	64.3	Peak type trace
90	Zr/Black NiO Fluorel Lot EL 37036	22.85	0.327	3.44	0.18	22.2	58.8	Peak type trace
91		20.77	0.300	3.41	0.19	12.3	32.6	Peak type trace
35	Mg/Halon Fluorel (1960 Mix) Lot N 39545	11.66	0.295	1.95	0.03	17.0	45.0	Very consistent trace
49		14.09	0.358	1.94	0.04	19.8	52.4	Very consistent trace
50		14.14	0.360	1.94	0.04	19.8	52.4	Very consistent trace
71		14.84	0.377	1.94	0.04	19.0	50.3	Fairly consistent trace
72		14.89	0.377	1.94	0.03	19.6	51.9	Very consistent trace
73		14.81	0.377	1.94	0.04	19.0	50.3	Very consistent trace
74		14.60	0.376	1.94	0.03	18.4	48.7	Fairly consistent trace
75		14.94	0.370	1.89	0.03	18.0	47.6	Very consistent trace
76		14.79	0.376	1.94	0.03	19.2	50.8	Fairly consistent trace
125		15.01	0.379	1.95	0.03	16.6	43.9	Very consistent trace
127		14.97	0.380	1.94	0.03	15.6	41.3	Very consistent trace
128		14.97	0.380	1.93	0.03	16.0	42.4	Very consistent trace
137	Mg/B Teflon Fluorel Lot EL 37056	14.91	0.377	1.95	0.05	15.5	41.0	Very consistent trace
138		14.85	0.376	1.94	0.05	15.6	41.3	Very consistent trace
139		14.82	0.376	1.94	0.05	20.3	53.7	Fairly consistent trace
140		14.87	0.377	1.94	0.06	21.3	56.4	Somewhat erratic trace
145	Mg Mo ₃ Fluorel Lot EL 37061	17.84	0.386	2.30	0.46	18.0	47.6	Peak type trace
146		17.81	0.388	2.28	0.43	18.0	47.6	Peak type trace
147		17.68	0.385	2.28	0.41	18.0	47.6	Peak type trace
164	Mg/Teflon Fluorel (Stoichiometric) Lot EL 37041	14.82	0.363	2.01	0.03	17.6	46.6	Very consistent trace
165		14.84	0.363	2.01	0.03	17.1	45.3	Fairly consistent trace
81	Zr Mo ₃ Fluorel Lot EL 37035	24.56	0.279	4.34	0.10	15.0	39.7	Somewhat erratic trace
82		24.69	0.280	4.35	0.11	16.7	44.2	Very erratic trace
83		24.70	0.280	4.35	0.10	12.0	31.8	Peak type trace
43	Zr Mo ₃ Fluorel Lot EL 37028	26.25	0.297	4.36	0.11	11.0	29.1	Somewhat erratic trace
45		26.20	0.296	4.37	0.11	12.5	33.1	Somewhat erratic trace
23	Al/KClO ₄ /Black NiO/ Halon Fluorel (SMP-61A) Lot EL 29990-C	19.73	0.383	2.54	0.06	11.6	30.7	Very consistent trace
24		19.71	0.383	2.54	0.05	9.6	25.4	Very consistent trace
48		19.52	0.382	2.52	0.06	12.3	32.6	Very consistent trace
39	Al/KClO ₄ /Sm ₂ /Halon/ Fluorel Lot EL 34177	14.88	0.273	2.69	0.04	9.6	25.4	Consistent oscillating trace
40		14.88	0.273	2.69	0.04	12.0	31.8	Consistent oscillating trace
41		14.86	0.273	2.68	0.04	11.5	30.4	Consistent oscillating trace
36	Al/KClO ₄ /Tep ₃ O ₅ /Halon/ Fluorel Lot EL 34174	15.69	0.284	2.55	0.04	10.1	26.7	Very consistent trace
37		15.66	0.284	2.55	0.04	10.8	28.6	Very erratic trace
38		14.82	0.284	2.55	0.04	11.4	30.2	Very consistent trace

CANDIDATE PYROTECHNICS IN DECREASING ORDER OF
EFFECTIVENESS AS RADIANT EMITTERS

Test No. (S/N)	Composition	Pellet Weight (gm)	Pellet Thickness (in)	Pellet Density (gm/cm ³)	Pellet Burn Rate (in/sec)	Maximum Measured Irradiance (mw/cm ²)	Maximum Calculated Source Irradiance (cal/cm ² /sec)	Remarks
189 190 191	Mg/Zr/MoO ₃ /Fluorel Lot EL 40104	19.95 20.00 19.94	0.346 0.351 0.344	2.87 2.88 2.88	0.69 0.70 0.69	30.8 31.0 21.5	81.5 82.1 56.9	Peak type trace, rapid burn Peak type trace, rapid burn Peak type trace, rapid burn
159 160 161 162	Mg/Zr/MoO ₃ Fluorel Lot EL 37081	22.01 21.83 22.13 21.91	0.374 0.403 0.408 0.403	2.93 2.70 2.70 2.70	0.37 0.67 0.58 0.67	27.0 22.0 29.0 27.0	71.5 58.2 76.8 71.5	Peak type trace, rapid burn Peak type trace, rapid burn Peak type trace, rapid burn Peak type trace, rapid burn
209 210 211 212	Zr/MoO ₃ /Fluorel Lot EL 40130	23.23 23.00 23.19 23.66	0.298 0.296 0.298 0.301	3.88 3.85 3.87 3.91	0.13 0.11 0.10 0.10	16.4 29.6 21.0 31.0	43.4 78.4 55.6 82.1	Fairly consistent trace Fairly consistent trace Fairly consistent trace Fairly consistent trace
192 193 194	Mg/Zr/MoO ₃ /Fluorel Lot EL 40105	19.84 20.07 20.00	0.397 0.403 0.398	2.49 2.48 2.51	0.79 0.81 0.80	24.0 22.3 23.4	63.5 59.0 61.9	Peak type trace, rapid burn Peak type trace, rapid burn Peak type trace, rapid burn
170 171 172	Mg/Halon/Fluorel Lot EL 37070 (1960 Mix)	15.24 15.21 15.17	0.387 0.389 0.385	1.96 1.94 1.96	0.03 0.03 0.03	16.8 16.2 19.2	44.5 42.9 50.8	Very consistent trace Very consistent trace Very consistent trace
186 187 188		15.08 15.10 15.06	0.390 0.391 0.390	1.92 1.92 1.92	0.03 0.03 0.03	17.1 17.0 16.1	45.3 45.0 42.6	Fairly consistent trace Fairly consistent trace Fairly consistent trace
203 204		15.03 15.04	0.387 0.387	1.93 1.93	0.03 0.03	14.0 16.2	37.1 42.9	Very consistent trace Very consistent trace
205 206 207 208		15.09 15.03 15.06 15.15	0.391 0.385 0.386 0.391	1.92 1.94 1.94 1.92	0.03 0.03 0.03 0.03	15.6 18.6 15.6 17.4	41.3 49.2 41.3 46.1	Fairly consistent trace Fairly consistent trace Fairly consistent trace Fairly consistent trace
199 200 201 202	Mg/Zr/MoO ₃ Fluorel Lot EL 40125	23.01 23.01 23.02 22.94	0.382 0.382 0.381 0.380	2.99 2.99 3.00 2.99	0.20 0.18 0.20 0.20	18.1 17.4 17.3 16.5	47.7 46.1 45.8 43.7	Very consistent trace Very consistent trace Very consistent trace Very consistent trace
155 156 157 158	Mg/Zr/Teflon/Fluorel Lot EL 37080	17.16 17.05 17.40 17.23	0.364 0.363 0.371 0.366	2.34 2.34 2.33 2.34	0.02 0.02 0.02 0.02	13.8 15.0 15.6 13.5	36.5 39.7 41.3 35.7	Fairly consistent trace Somewhat erratic trace Very consistent trace Fairly consistent trace
163 164 165 166 167	Al/KClO ₄ /Ba(NO ₃) ₂ /Fluorel Lot EL 37089	15.28 15.16 15.27 15.21 15.30	0.335 0.332 0.338 0.337 0.336	2.27 2.27 2.25 2.25 2.27	0.03 0.03 0.03 0.03 0.03	14.0 13.8 10.8 14.4 9.9	37.1 36.5 28.6 38.1 23.8	Fairly consistent trace Very consistent trace Fairly consistent trace Fairly consistent trace Fairly consistent trace
195 196 197 198	Zr/MoO ₃ /Fluorel Lot EL 40124	23.30 23.27 23.27 23.44	0.289 0.290 0.291 0.292	4.00 3.98 3.96 3.98	0.07 0.07 0.07 0.07	12.1 11.2 12.6 11.4	32.0 29.7 33.4 30.2	Very consistent trace Fairly consistent trace Fairly consistent trace Fairly consistent trace

Test:

Viewing aperture radius in all tests was 0.95 cm.

Distance between pyrotechnic pellet and detector surface was 100 cm.

In all tests, the pellet was positioned so that its surface was 0.5 cm below and 2.0 cm away from the viewing aperture.

Ignition was accomplished in all tests with 430 ignition powder and an M-100 electric match.

During Test No.'s 191 and 209, the plumes were inadvertently canted away from the aperture.

Test No. (S/N)	Composition	Pellet Weight (gm)	Pellet Thickness (in)	Pellet Density (gm/cm ³)	Pellet Burn Rate (in/sec)	Maximum Measured Irradiance (mw/cm ²)	Maximum Calculated Source Irradiance (cal/cm ² /sec)	Remarks
123	Mg/Teflon/Fluorel	15.00	0.406	1.82	0.07	8.0	21.1	Fairly consistent trace
124	(1340 Ignition Mix)	15.10	0.409	1.82	0.08	8.8	23.3	Fairly consistent trace
125	Lot N 39536-8	15.19	0.410	1.82	0.07	7.7	20.4	Very consistent trace
117	Ti/MoO ₃ /Fluorel	19.64	0.313	3.09	0.05	6.8	18.0	Very erratic trace
118	Lot EL 37005	19.73	0.313	3.11	0.05	7.8	20.6	Very erratic trace
119		19.67	0.311	3.12	0.06	7.8	20.6	Very erratic trace
51	Al/CaSO ₄ · 2H ₂ O	10.56	0.311	1.56	0.15	9.2	24.4	Somewhat erratic trace
52	Lot EL 37030	9.70	0.279	1.60	0.14	6.4	16.9	Peak type trace
53		10.35	0.302	1.58	0.14	4.3	11.4	Very erratic trace
120	Mg/Halon/Fluorel/	14.94	0.402	1.83	0.05	5.1	13.5	Very consistent trace
121	Pb ₃ O ₄	14.92	0.402	1.83	0.05	7.0	19.5	Somewhat erratic trace
122	(50-3052 Ignition Mix)	14.91	0.400	1.83	0.05	7.4	19.6	Fairly consistent trace
120	Lot 1370							
28	Al/KClO ₄ /Fluorel	12.34	0.290	2.10	0.04	6.9	18.3	Very erratic trace
29	Lot EL 37013	12.33	0.290	2.10	0.04	6.4	16.9	Very erratic trace
30		12.34	0.289	2.10	0.04	6.5	17.2	Very erratic trace
134	Zr/CaSO ₄ · 2H ₂ O	19.65	0.400	2.27	0.09	2.9	7.7	Long peak type trace
135	Lot EL 37055	19.89	0.405	2.27	0.08	5.7	15.1	Long peak type trace
136		20.32	0.410	2.29	0.08	4.6	12.2	Long peak type trace
98	Ta/MoO ₃ /Fluorel	24.91	0.222	5.53	0.05	5.1	13.5	Long peak type trace
99	Lot EL 37039	24.89	0.222	5.53	0.03	4.0	10.6	Long peak type trace
31	Mg/NaNO ₃ /Fluorel	11.04	0.299	1.82	0.11	4.2	11.1	Very consistent trace
32	Lot EL 37015	11.00	0.298	1.82	0.11	4.8	12.7	Fairly consistent trace
33		10.98	0.297	1.82	0.11	4.9	13.0	Fairly consistent trace
42		10.77	0.294	1.81	0.11	4.5	11.9	Very consistent trace
47		11.56	0.313	1.82	0.11	4.5	11.9	Fairly consistent trace
9	Al/KClO ₄ /Fe ₂ O ₃ /	14.95	0.320	2.30	0.03	3.1	8.2	Very erratic trace
10	MnO ₂ /Halon/Fluorel	15.04	0.319	2.33	0.03	2.5	6.6	Very erratic trace
13	Lot EL 34176	14.80	0.315	2.32	0.03	3.0	7.9	Very erratic trace
15		14.78	0.315	2.31	0.03	2.9	7.7	Very erratic trace
85		14.91	0.315	2.33	0.03	3.9	10.3	Very erratic trace

NOTES:

1. In all tests, the pyrotechnic pellet diameter was 1.25 inches.
2. The distance between the pyrotechnic pellet and the detector surface was 100 cm in all tests except S/N 59. In S/N 59 this distance was 150 cm.
3. In all tests, the viewing aperture radius was 0.95 cm.
4. In all tests, the pellet was positioned so that its surface was 0.5 cm below and 2.0 cm away from the viewing aperture.
5. Ignition was accomplished using either 3 grams of 430 ignition powder or 3 grams of 430 ignition powder plus 1 gram of SP-61A. The SP-61A was required to ignite Al/CaSO₄ · 2H₂O, Zr/CaSO₄ · 2H₂O, and Ta/MoO₃/Fluorel.
6. A reflector consisting of steel shim stock (0.010 inch) affixed to an asbestos board was placed behind the pellet/holder assembly in S/N's 62, 63, and 64.
7. A 2 inch by 2 inch by 1/8 inch protective quartz plate was placed over the detector field-stop aperture in S/N's 72, 73, 74, and 75.